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Automatic high speed excitation of a synchronous generator

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Massachusetts Institute of Technology

AUTOMATIC HIGH SPEED EXCITATION
OF A SYNCHRONOUS GENERATOR

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WILLIAM R. RIBLETT

Cambridge, Massachusetts
May 20, 1949

Professor J. S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled, "Automatic High Speed Excitation of a Synchronous Generator."

Respectfully,

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Lieutenant,
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AUTOMATIC HIGH SPEED EXCITATION OF A SYNCHRONOUS GENERATOR

by

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(1942)

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Submitted in Partial Fulfillment

of the Requirements for the Degree of

Naval Engineer

from the

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1949

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I SUMMARY

The fundamental purpose of automatic high-speed excitation of a synchronous machine is to increase its stability. This can be accomplished by supplying a component of field current that is proportional to power angle. Another component of field current proportional to rate of change of power angle is required to act as a damping force on any oscillations that may be set up in the machine. In this thesis the effects of these two components on a particular salient-pole generator were studied, using various proportionality factors between field current and power angle.

The results show curves of power vs. power angle and field current vs. power angle for three different proportionality factors between the compensating component of the field current and the power angle. Each of these is shown with four different components of steady-state field current. It was found that the range of stability increased by about five degrees when compensation proportional to power angle was used and by about ten degrees when compensation proportional to both power angle and rate of change of power angle was used.

The experimental results verified the fact that compensation proportional to rate of change of power angle was required. When compensation proportional to power angle alone was used, the system was highly oscillatory, but the addition of the compensation proportional to rate of change of power angle damped out the oscillations.

From the results it can be concluded that it is entirely feasible to operate a machine using this type of excitation at power angles greater than that at which maximum power occurs for any given fixed field current. However, the system would have to be designed with very fast response and with components large enough to eliminate saturation effects.

Further studies along this line are recommended with particular emphasis on operation at very large power angles, i.e. ninety degrees or more. An investigation into the effects of this system when the generator is driving a synchronous motor would also be desirable, since this thesis has been limited to operation against a substantially infinite bus.

II INTRODUCTION

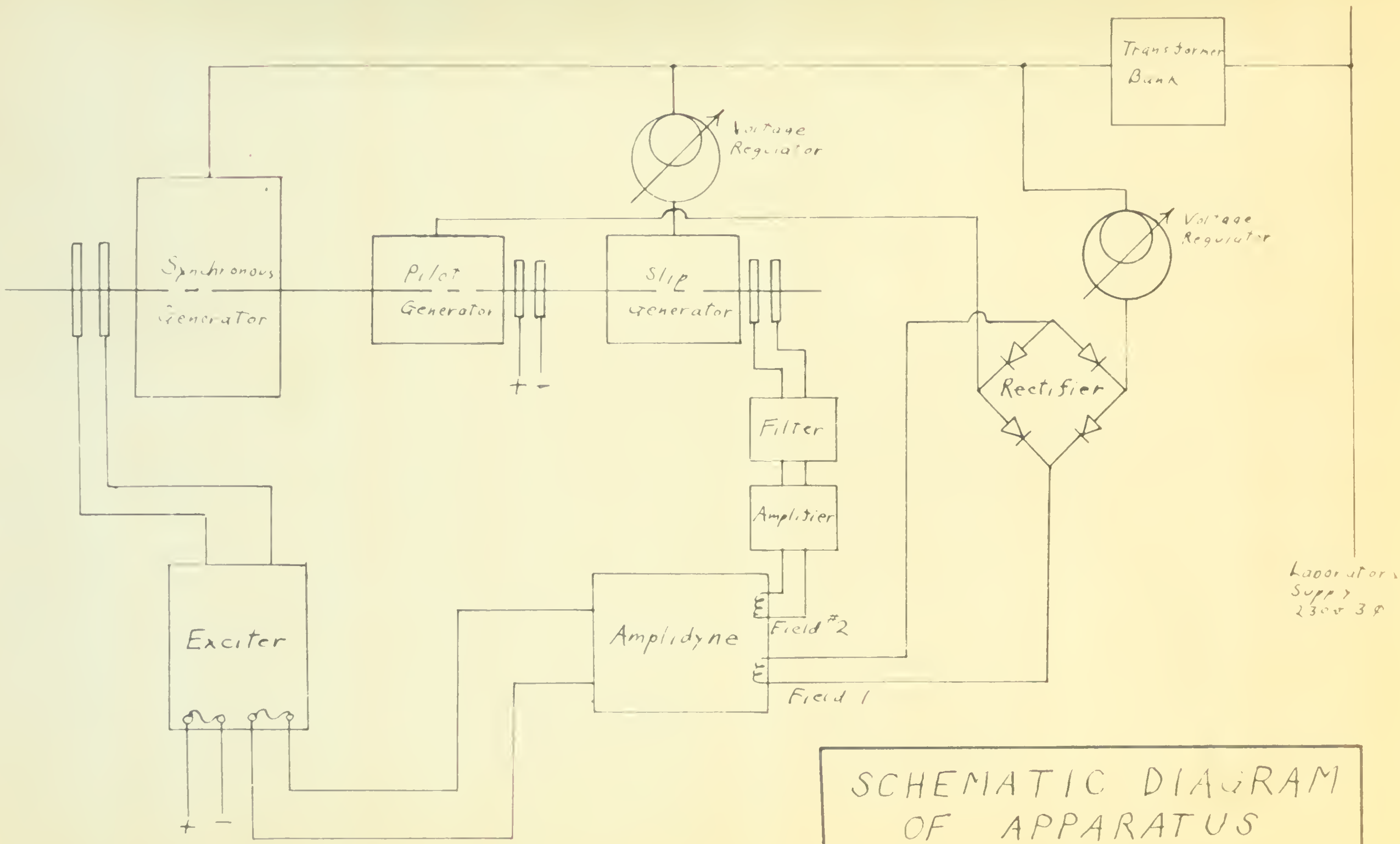
In the decade following World War I the rapid growth of electric power systems introduced the problem of power system stability. Transmission of power over long distances caused the power angle between the rotors of synchronous machines to increase to a point where sudden additions of load might knock the generators out of synchronism before additional generators could be put on the line. This problem was partially solved by the use of improved relays and circuit breakers.

In the past decade attempts to use even longer transmission lines and to utilize existing generation facilities more effectively have again brought system stability problems to the fore. The following three methods of improving steady-state stability (i.e., ability to carry small increases in load) have been studied: (1) use of static or synchronous condensers at intermediate points to reduce the power angle, (2) use of asynchronous generators, in which the alternator field is supplied with low-frequency alternating current, and (3) use of standard alternators with a d-c field upon which is superimposed a current which is varied automatically by changes of power angle.

Brown-Boveri Company of Switzerland has conducted stability investigations following method (3) above. Their papers on the subject ([1] and [2]) show the worth of the automatic excitation method in general. This thesis deals with the application of

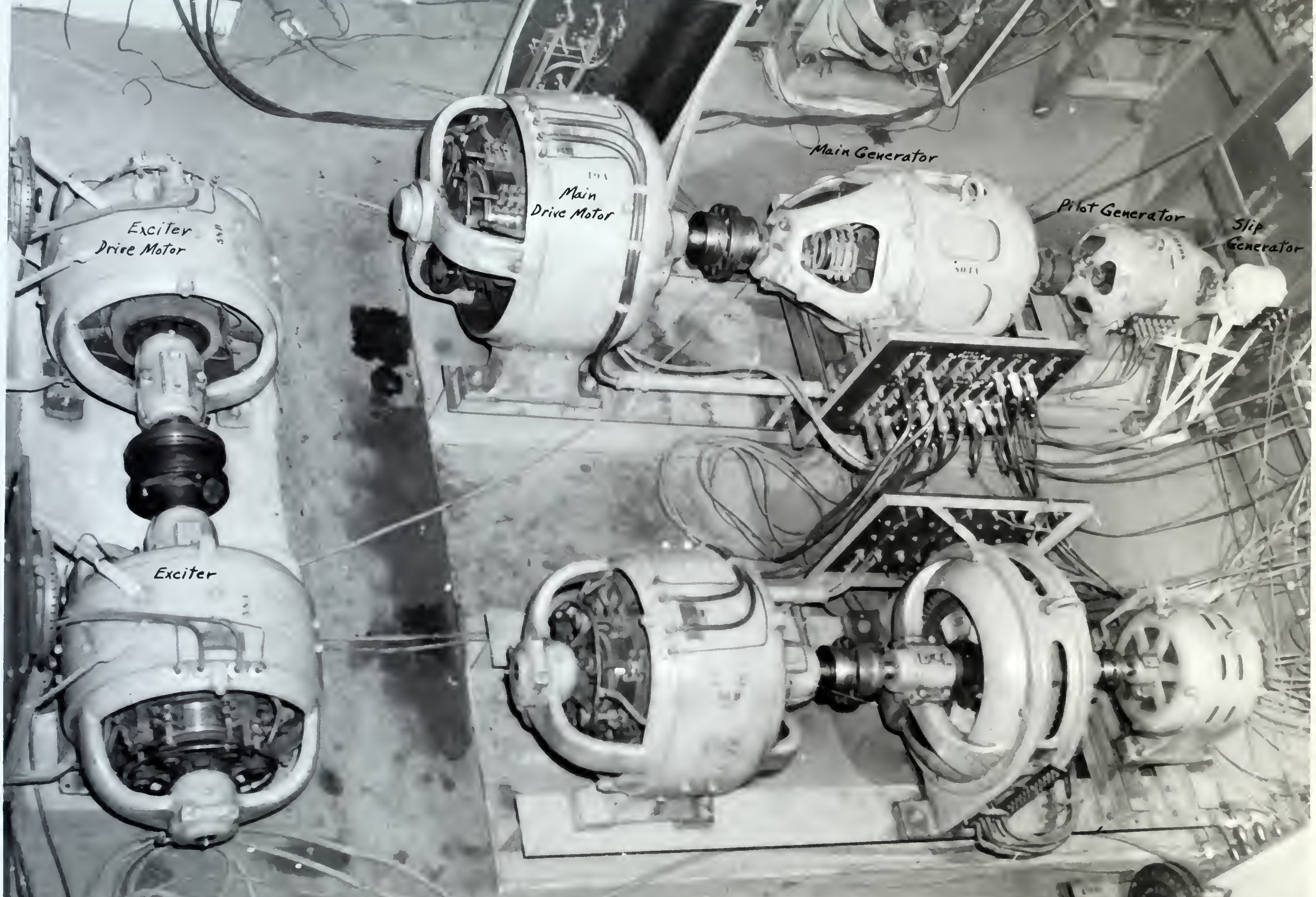
this method of excitation to a particular salient-pole alternator operating against an infinite bus, showing the effects of controlling excitation first by change of power angle alone and then by a combination of change and rate of change of power angle. In this case power angle is taken as the phase angle between terminal voltage and the voltage behind synchronous reactance.

The component of the exciting current depending upon the change of power angle is obtained from the vector difference of the line voltage and the stator voltage of a pilot generator. The component depending upon the rate of change of power angle is obtained from the rotor voltage of a small wound rotor induction motor mounted on the same shaft as the alternator and pilot generator. These two components are fed into the two control fields of an amplidyne, whose output is in turn fed into one field of a two-field exciter. The other field of the exciter provides the steady-state component of the generator field. A schematic diagram of the apparatus is shown in Figure 1.



SCHEMATIC DIAGRAM OF APPARATUS

FIGURE 1


Main Generator
Pilot Generator
Slip Generator
Main Drive Motor
Exciter Drive Motor
Exciter
PLATE I

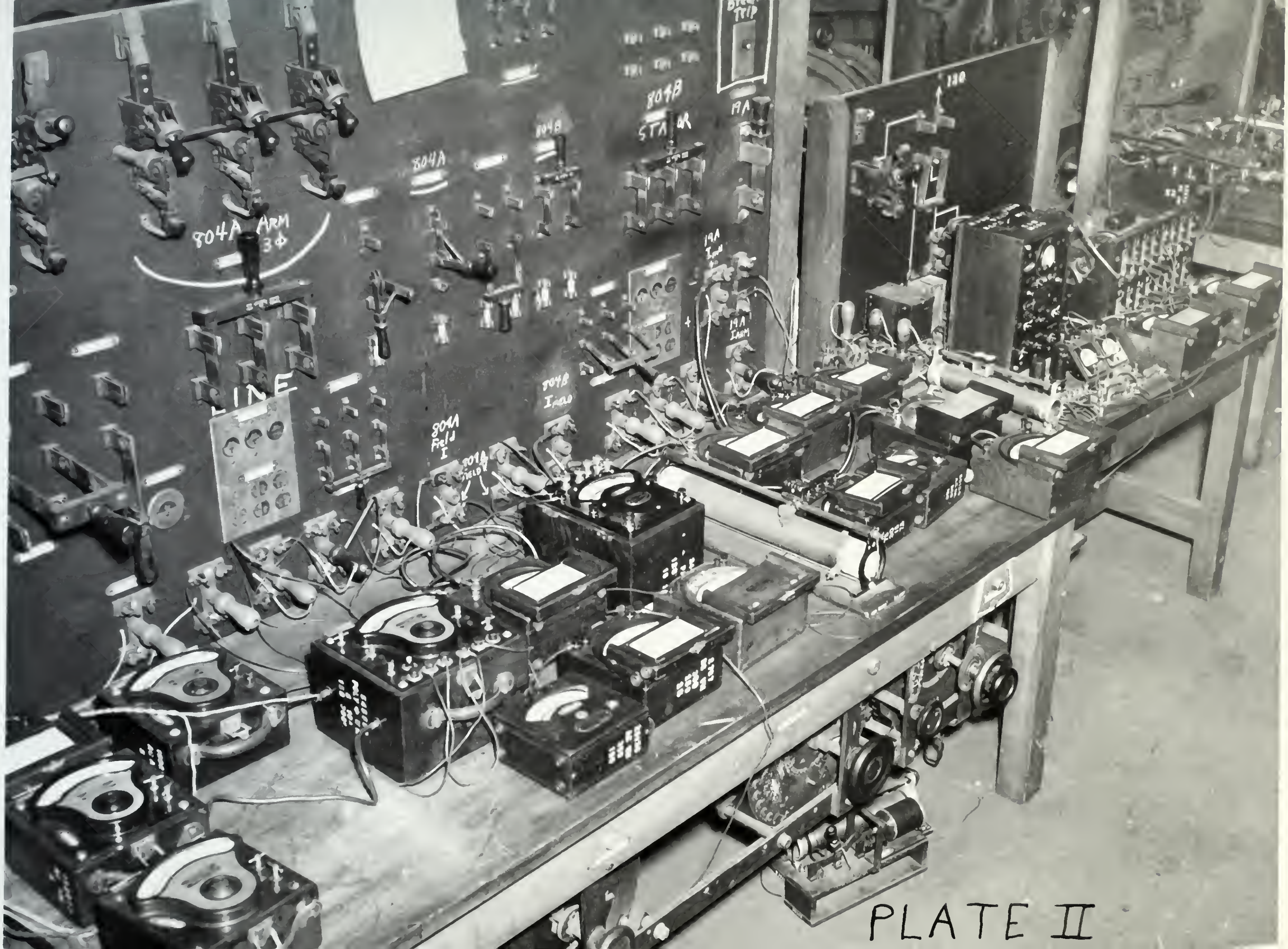

804A ARM 3Φ
LINE
804A
804B
804B STATOR
19A
804B I FIELD
804A Field I

PLATE II

III PROCEDURE

A total of four tests was made to study the effects of various types of automatic excitation on the relation between power output and power angle.

Test 1 was made with no automatic excitation, supplying the main generator field simply by exciting one field of the exciter with a constant direct voltage. Nine such runs were made, varying the alternator field current from the minimum possible value of 3.6 amperes to 7.5 amperes. In each run the load was increased by decreasing the field of the driving motor until either the alternator fell out of synchronism or the current rating of the alternator was reached.

In test 2 automatic excitation proportional to power angle was introduced by exciting the field of the pilot generator and adjusting the three-phase variac to place voltages of equal magnitude across the rectifier, thus exciting one field of the amplidyne. The same proportionality factor between power angle and the variable component of alternator field current was used in the first three runs by fixing the stator voltage of the pilot generator. Three widely varying values of steady state exciter field current were used in these runs to demonstrate the effects of different ratios of fixed and variable components of alternator field current. Two other sets of three runs each were made, using a different value of pilot generator stator voltage for each set of runs. Thus the nine runs of test 2

covered all possible combinations of the three values used for steady state exciter field current and the three values used for pilot generator stator voltage which in turn determines the variable exciter field current.

Additional automatic excitation proportional to rate of change of power angle was employed in test 3. This was accomplished by placing the stator of the induction machine (slip generator) across the line, amplifying the resultant rotor voltage, and applying the amplified voltage across the second control field of the amplidyne. The nine runs of test 2 were then repeated, again using all possible combinations of the three steady state exciter field currents and three pilot generator voltages used previously.

In tests 2 and 3 the fraction of the line voltage applied to one side of the rectifier was set approximately equal to the pilot generator stator voltage by adjusting the three-phase variac at the beginning of each run. Because the use of autotransformers in the line between the alternator and the laboratory three-phase supply resulted in rises in line voltage up to 10 per cent at rated alternator current, the magnitude of the voltage across the rectifier varied with load. Therefore, test 4 was made with both methods of automatic excitation in use, but with the further refinement that the magnitude of the voltage at the output of the variac was set continuously equal to the pilot

generator stator voltage. In this manner operation against an infinite bus was approximated as closely as possible with the equipment available. Care was also taken in this test to determine the exact maximum power angle at which the alternator would remain synchronized. The nine combinations of steady state exciter field current and pilot generator stator voltage used in tests 2 and 3 were again employed, but an additional six runs were made using two new steady-state values of exciter field current between the low and medium values previously used. Finally for each of these fifteen runs the automatic excitation proportional to $d\delta/dt$ was eliminated and the maximum power angle determined at which the alternator remained synchronized using excitation only.

In all tests, power was measured by a polyphase wattmeter after reducing the line currents by a factor of 40 through the use of current transformers. Power angle was determined by using a phase-angle meter to measure the phase angle between the pilot generator stator voltage and the current obtained by placing a resistor across one phase of the line.

IV RESULTS

Tests were made on a salient-pole alternator operating against an infinite bus (fixed potential line). With fixed alternator field current the maximum power angle which could be reached without loss of synchronism was about 80 degrees, the exact angle varying slightly with the magnitude of the field current. Addition of a second component of alternator field current proportional to power angle increased the maximum power angle obtainable to about 85 degrees, an increase of 5 degrees. Further addition of a third component of alternator field current proportional to rate of change of power angle increased the maximum power angle attainable to about 90 degrees, an overall increase of 10 degrees over the fixed excitation value.

All the power angles noted in the preceding paragraph are steady-state stability limits; i.e., the angles at which a very small increment of additional load will cause loss of synchronism. The numerical quantities given do not show completely the advantages of the automatically excited system. Another important factor is the amount of oscillation of the power angle about an average value, an oscillation which is present even when the load is constant. This fact was noted by observation of the phase angle meter used to measure power angle and also by stroboscopic observations of the alternator armature at constant load. Addition of compensation proportional to power angle alone increases slightly the

magnitude of oscillation of the power angle about a fixed value, while use of both components proportional to power angle and rate of change of power angle causes a sharp reduction in the magnitude of oscillation at power angles near the maximum. Thus it is apparent that the use of both components of compensation will permit stable operation of the alternator at power angle at least 10 degrees greater than would be possible with fixed excitation. (It should be noted that in neither case could the alternator be operated at a power angle near the maximum attainable without the use of standby generators and elaborate control equipment).

The curves of power and alternator field current as functions of power angle presented on the following pages show graphically the effects of changing (1) the proportionality factor between the first variable component of alternator field current and power angle, by changing the voltage on the pilot generator stator; and (2) the steady-state component of alternator field current, by changing the steady-state field current in the exciter. For comparison a set of curves of power as a function of power angle for various fixed alternator field currents is shown in Figure 2.

LIST OF CURVES

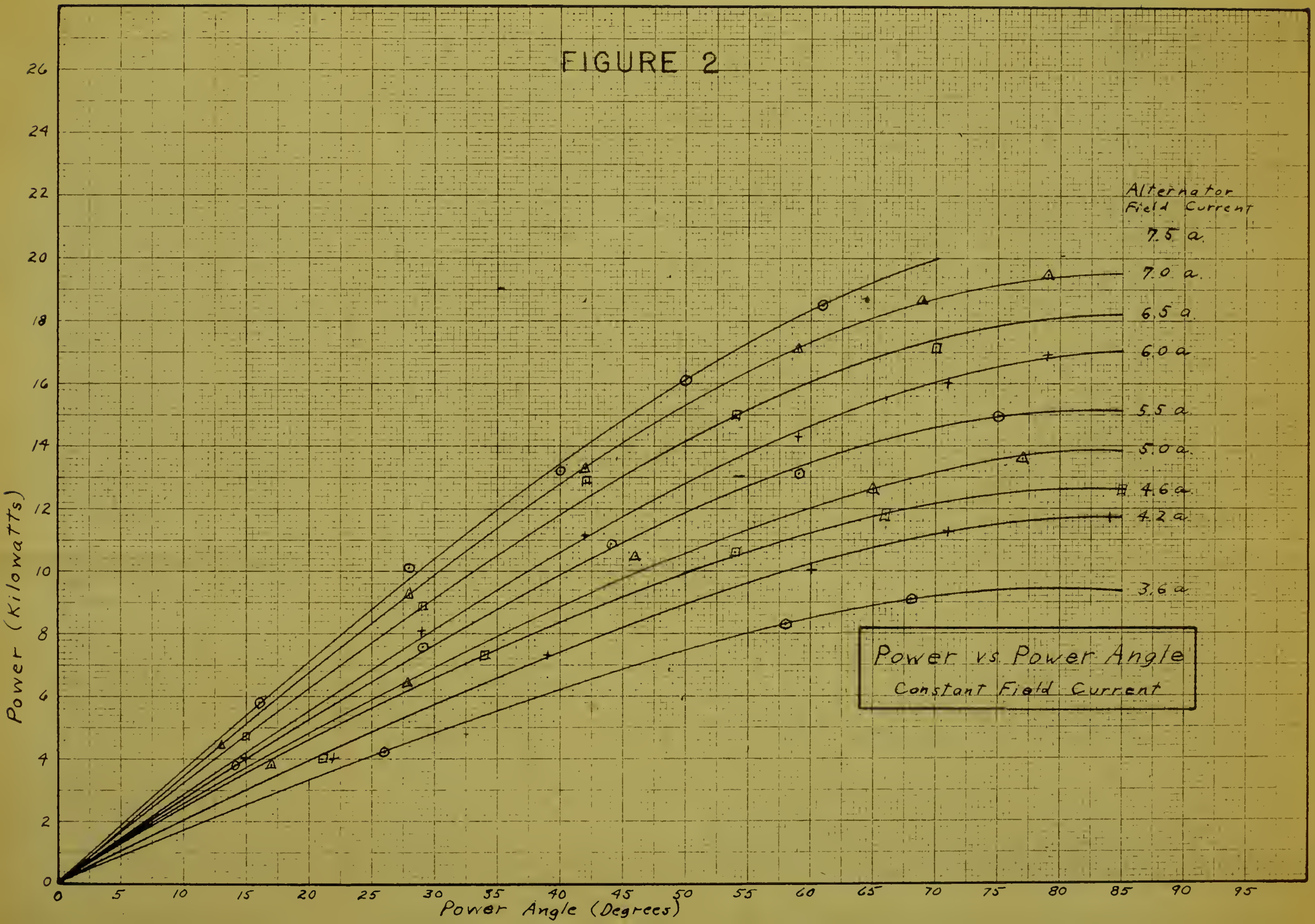


FIGURE 2
Alternator Field Current
7.5 a.
7.0 a.
6.5 a.
6.0 a.
5.5 a.
5.0 a.
4.6 a.
4.2 a.
3.6 a.
Power vs Power Angle
Constant Field Current
Power (Kilowatts)
Power Angle (Degrees)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

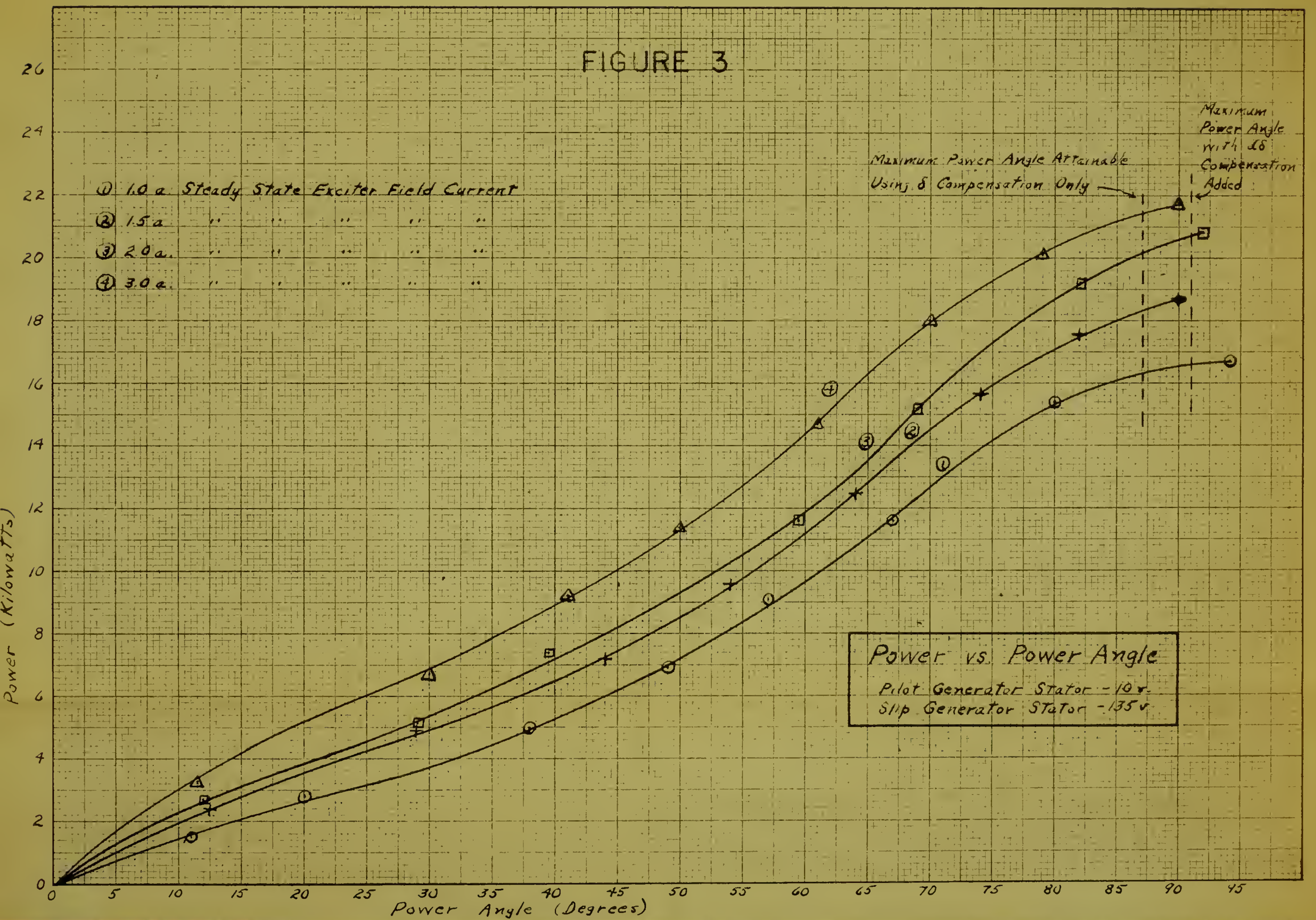


FIGURE 3
① 1.0 a Steady State Exciter Field Current
② 1.5 a " " " " "
③ 2.0 a. " " " " "
④ 3.0 a. " " " " "
Maximum Power Angle Attainable
Using δ Compensation Only
Maximum
Power Angle
with Δδ
Compensation
Added
Power vs. Power Angle
Pilot Generator Stator - 10 v.
Slip Generator Stator - 135 v
Power (Kilowatts)
Power Angle (Degrees)

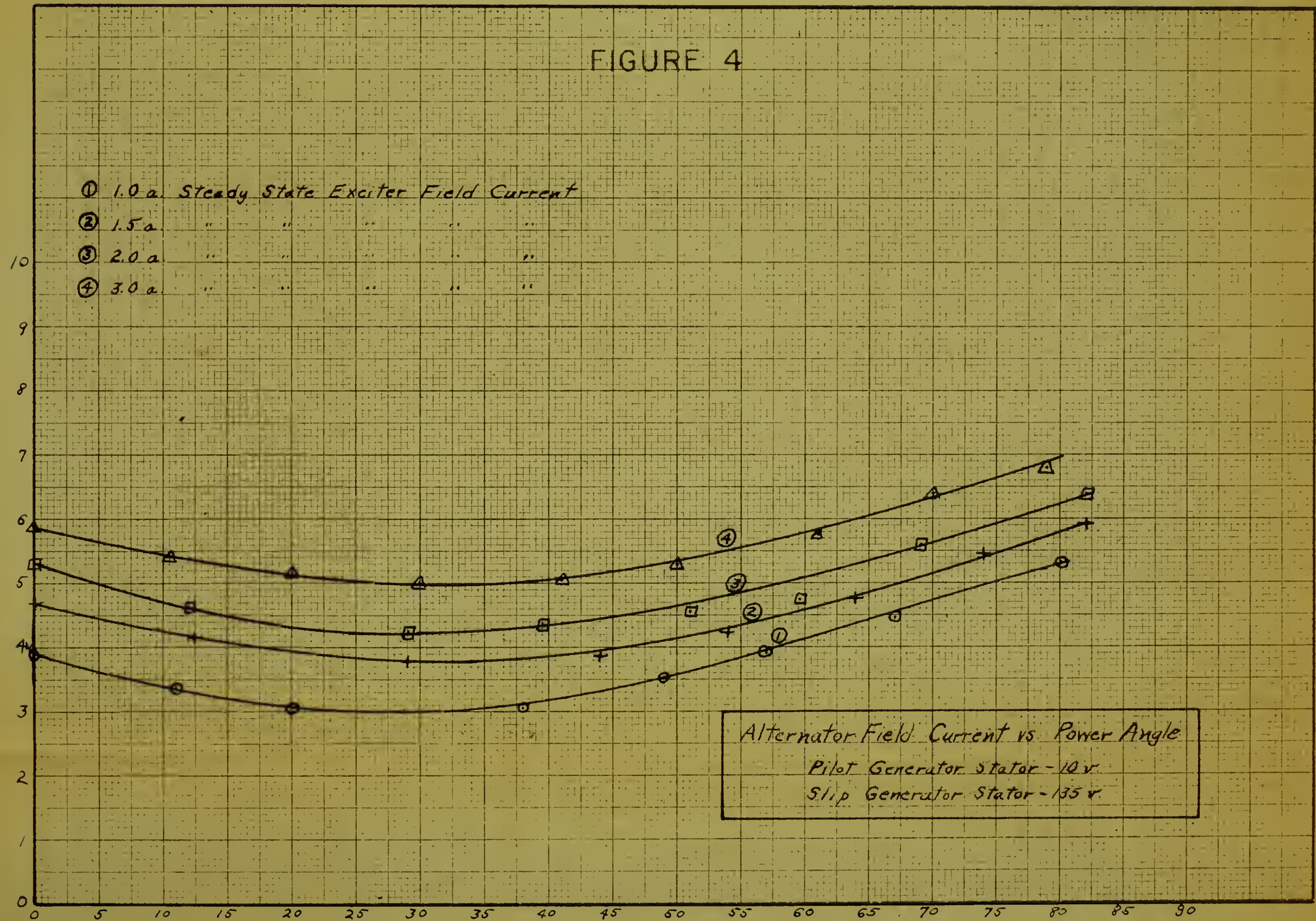


FIGURE 4
① 1.0 a. Steady State Exciter Field Current
② 1.5 a. " " " " "
③ 2.0 a. " " " " "
④ 3.0 a. " " " " "
Alternator Field Current vs Power Angle
Pilot Generator Stator - 10 v.
Slip Generator Stator - 135 v.
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

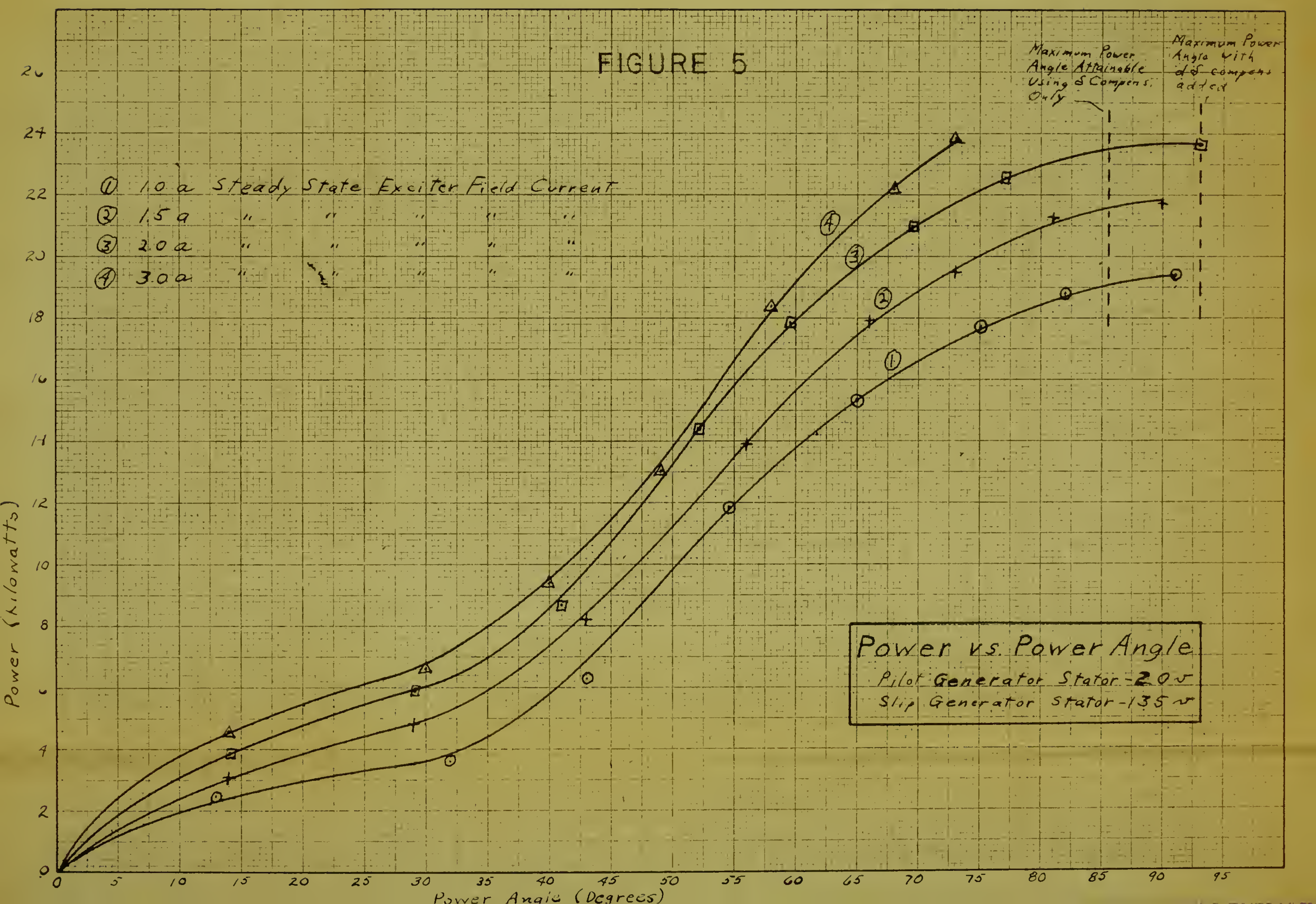


FIGURE 5
① 1.0 a Steady State Exciter Field Current
② 1.5 a " " " " "
③ 2.0 a " " " " "
④ 3.0 a " " " " "
Maximum Power Angle Attainable Using δ Compens. Only
Maximum Power Angle with dδ compens added
Power vs. Power Angle
Pilot Generator Stator - 20 v
Slip Generator Stator - 135 v
Power (kilowatts)
Power Angle (Degrees)

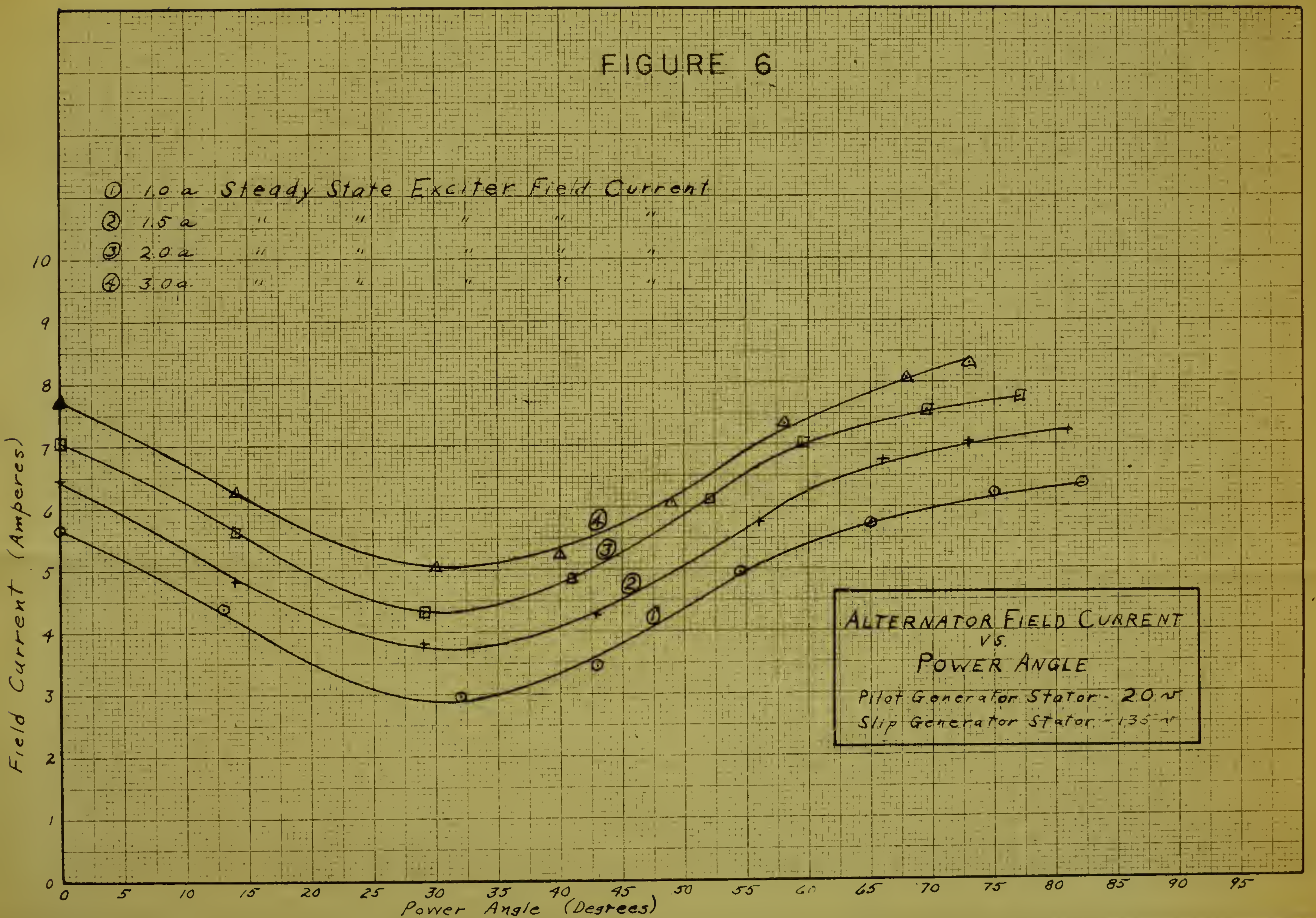


FIGURE 6
① 1.0 a Steady State Exciter Field Current
② 1.5 a " " " " "
③ 2.0 a " " " " "
④ 3.0 a " " " " "
ALTERNATOR FIELD CURRENT
VS.
POWER ANGLE
Pilot Generator Stator - 20 ~
Slip Generator Stator - 135 ~
Field Current (Amperes)
Power Angle (Degrees)
0
1
2
3
4
5
6
7
8
9
10
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

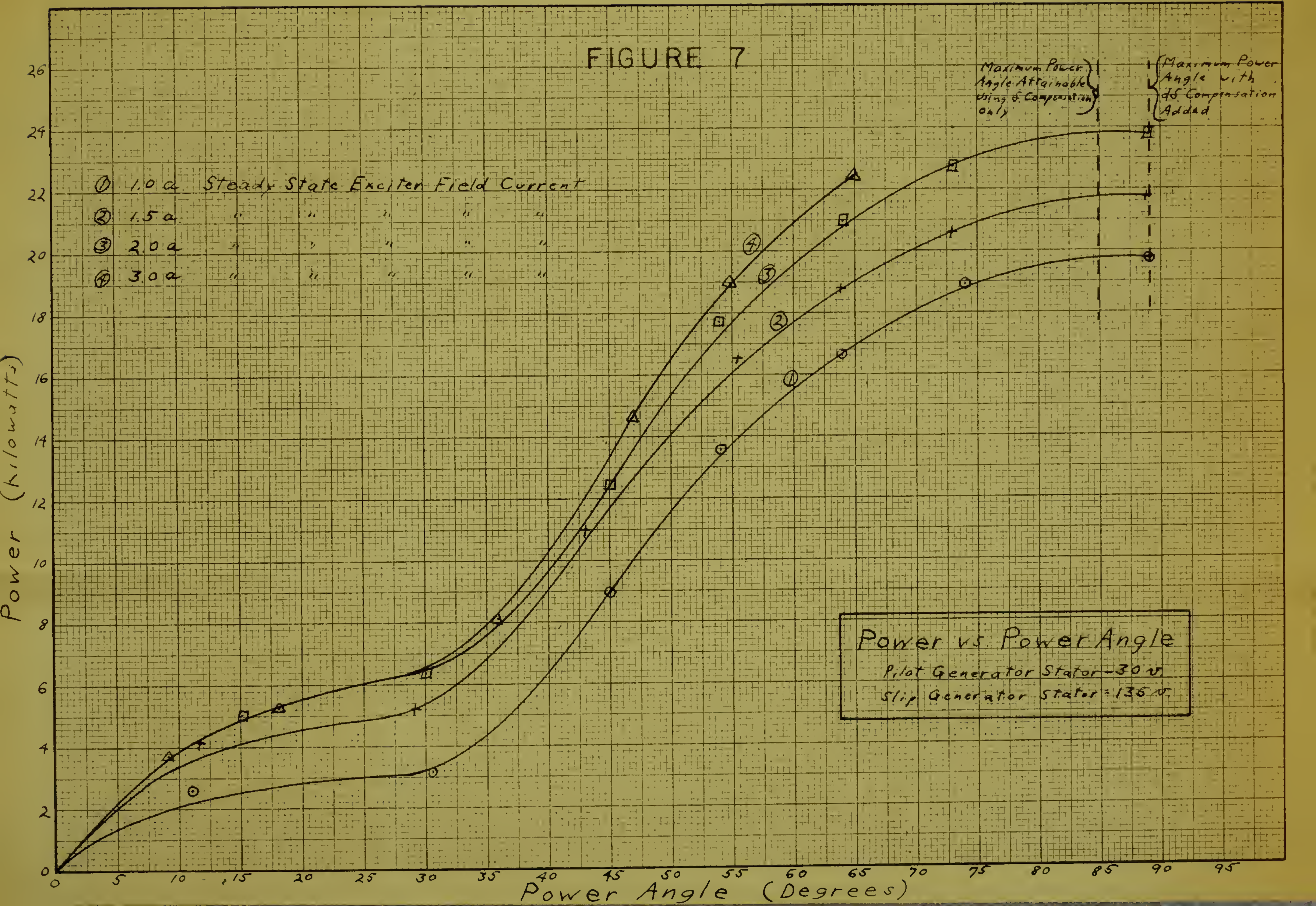
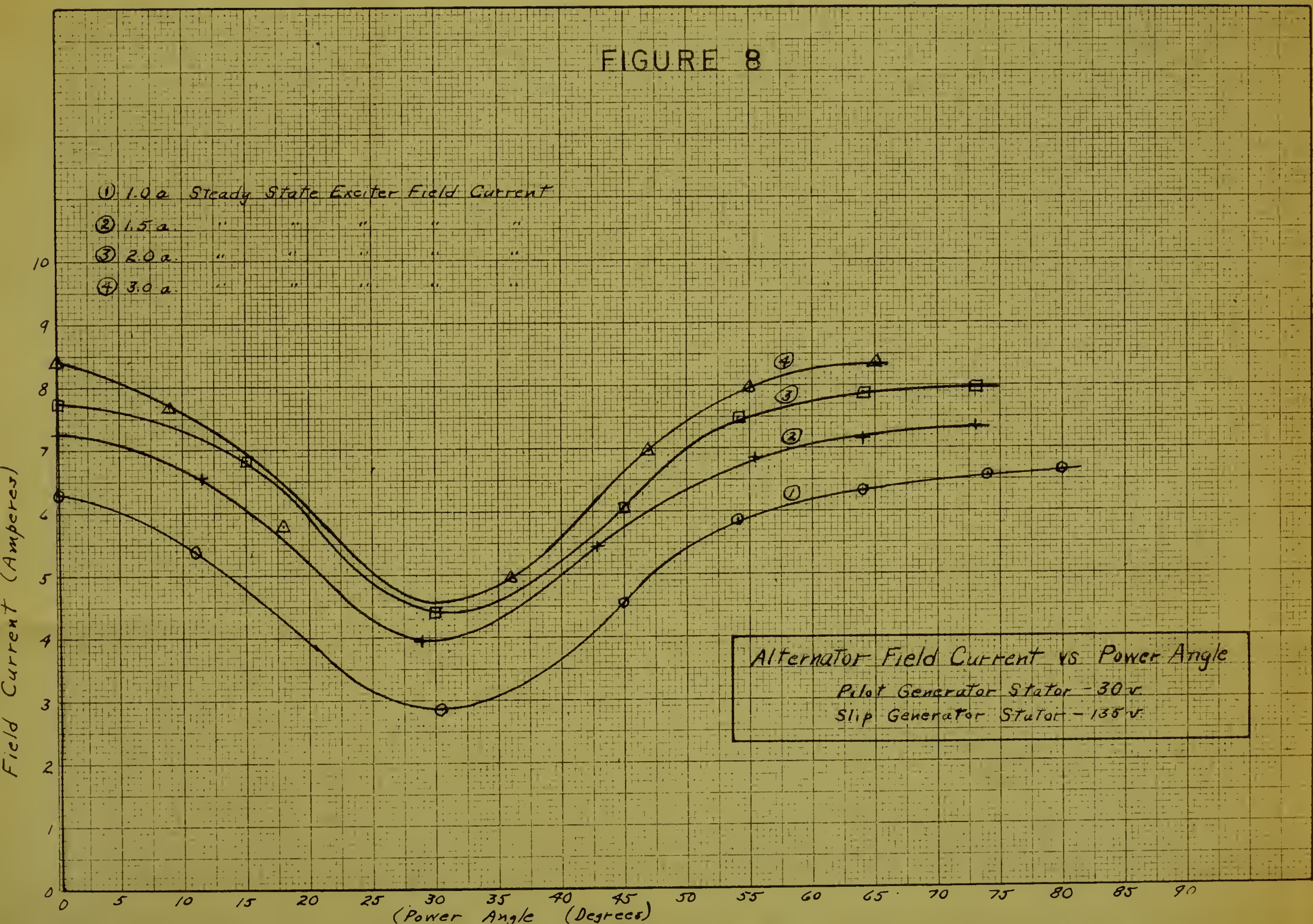


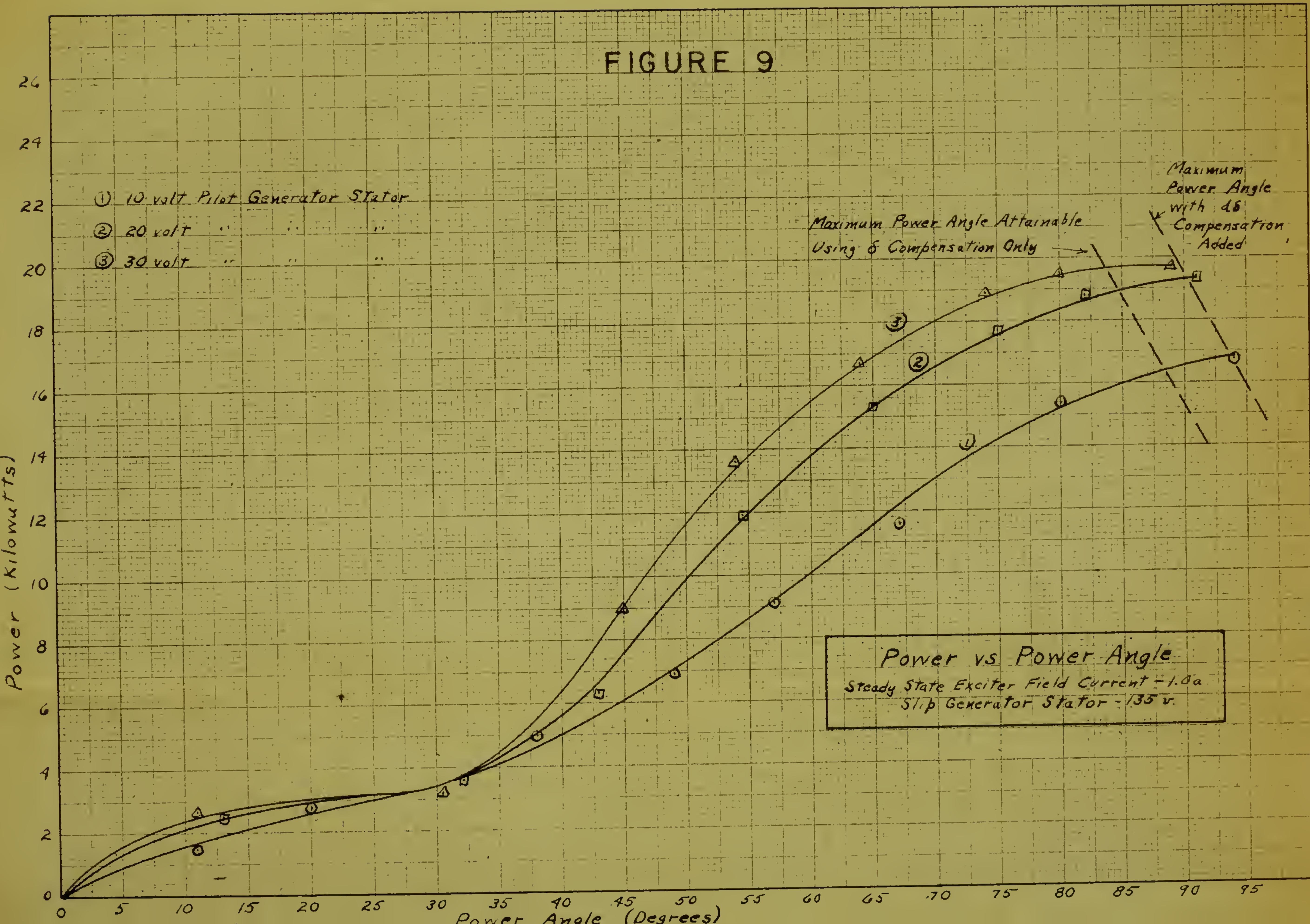
FIGURE 7
Maximum Power Angle Attainable Using δ Compensation only
Maximum Power Angle with dδ Compensation Added
① 1.0 a Steady State Exciter Field Current
② 1.5 a " " " " "
③ 2.0 a " " " " "
④ 3.0 a " " " " "
Power vs Power Angle
Pilot Generator Stator - 30 v
Slip Generator Stator = 136 v
Power (Kilowatts)
Power Angle (Degrees)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

FIGURE 8



① 1.0 a Steady State Exciter Field Current
② 1.5 a " " " " "
③ 2.0 a " " " " "
④ 3.0 a " " " " "
Alternator Field Current vs Power Angle
Pilot Generator Stator - 30 v.
Slip Generator Stator - 135 v.
Field Current (Amperes)
(Power Angle (Degrees)
0 1 2 3 4 5 6 7 8 9 10
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
①
②
③
④

FIGURE 9



① 10 volt Pilot Generator Stator
② 20 volt " " "
③ 30 volt " " "
Maximum Power Angle Attainable Using δ Compensation Only
Maximum Power Angle with dδ Compensation Added
Power vs Power Angle
Steady State Exciter Field Current - 1.0a
Slip Generator Stator - 135 v.
Power (Kilowatts)
Power Angle (Degrees)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

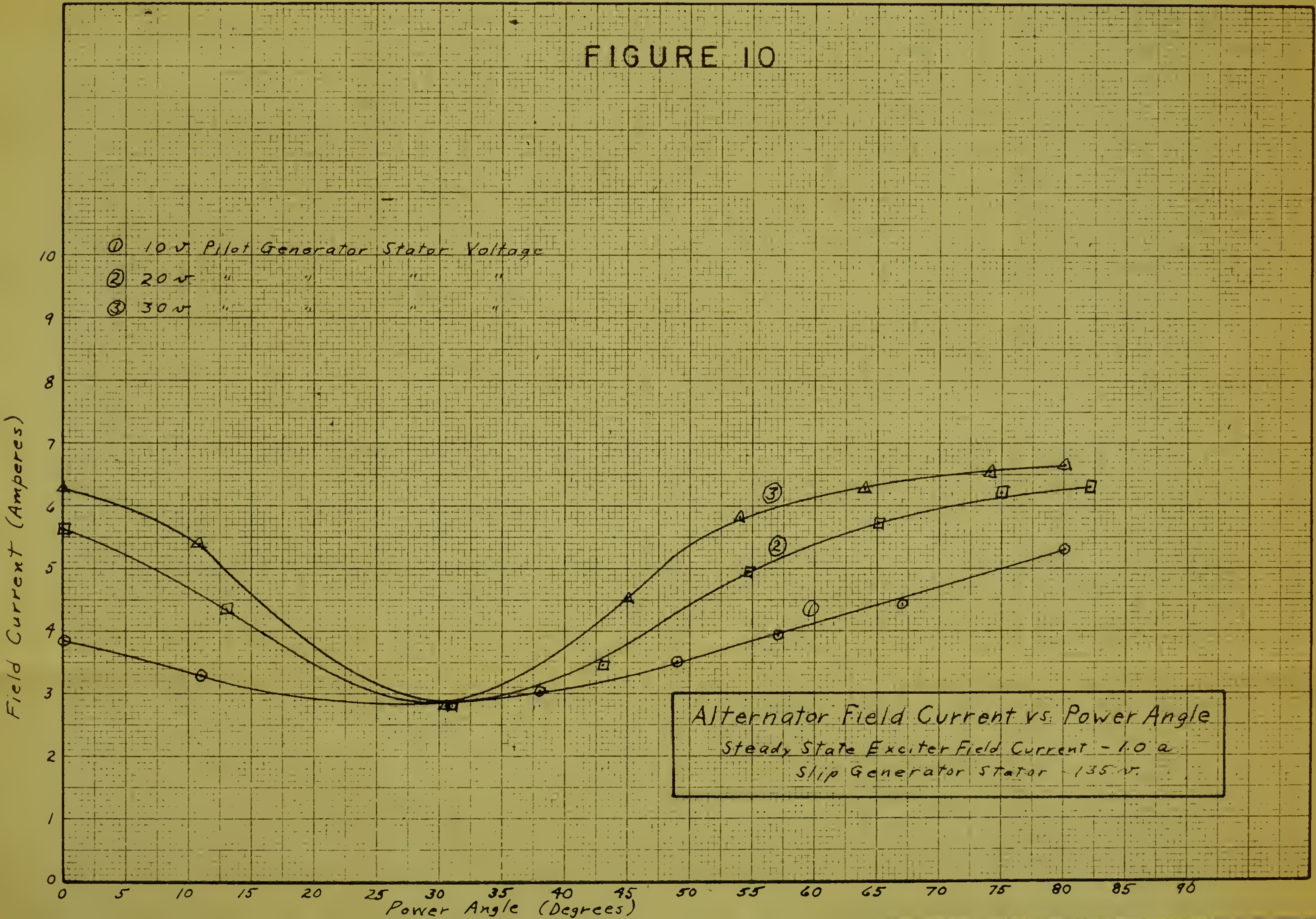


FIGURE 10
① 10 v Pilot Generator Stator Voltage
② 20 v " " " "
③ 30 v " " " "
Field Current (Amperes)
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Power Angle (Degrees)
Alternator Field Current vs Power Angle
Steady State Exciter Field Current - 1.0 a
Slip Generator Stator - 135 v.

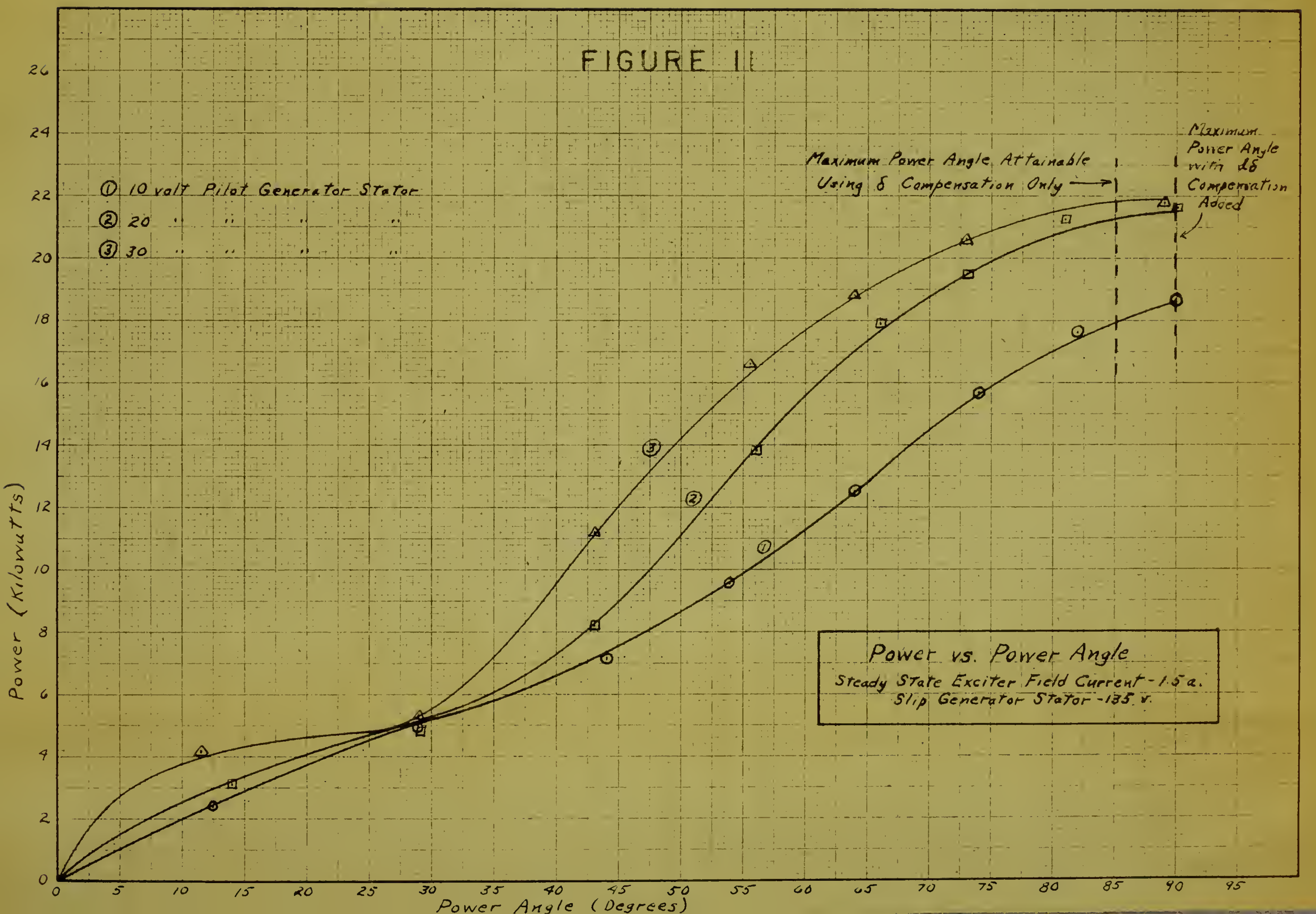
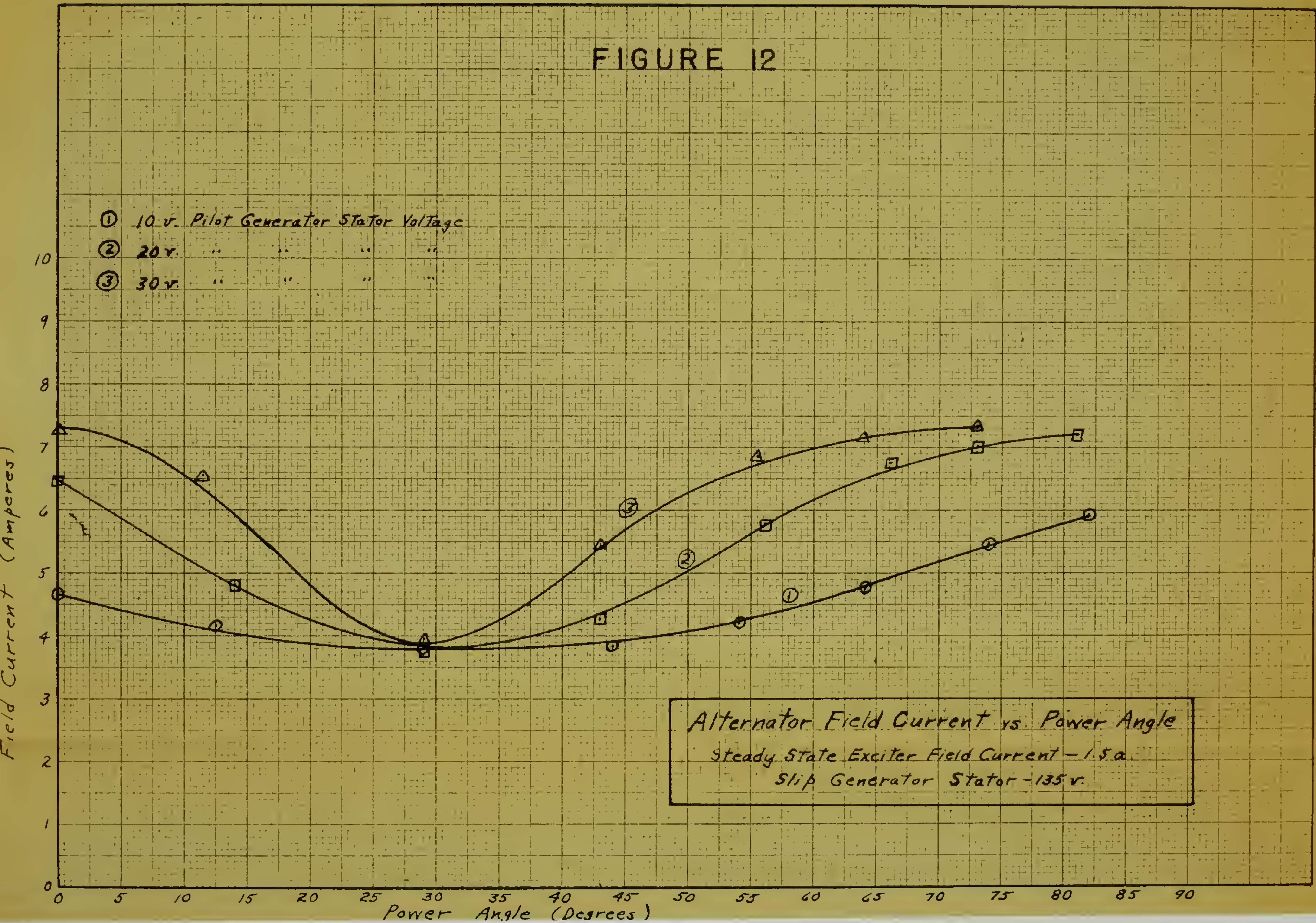


FIGURE II
① 10 volt Pilot Generator Stator
② 20 " " " "
③ 30 " " " "
Maximum Power Angle Attainable Using δ Compensation Only
Maximum Power Angle with dδ Compensation Added
Power vs. Power Angle
Steady State Exciter Field Current - 1.5 a.
Slip Generator Stator - 135 v.
Power (Kilowatts)
Power Angle (Degrees)

FIGURE 12



① 10 v. Pilot Generator Stator Voltage
② 20 v. " " " "
③ 30 v. " " " "
Alternator Field Current vs. Power Angle
Steady State Exciter Field Current – 1.5 a.
Slip Generator Stator – 135 v.
Field Current (Amperes)
Power Angle (Degrees)
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

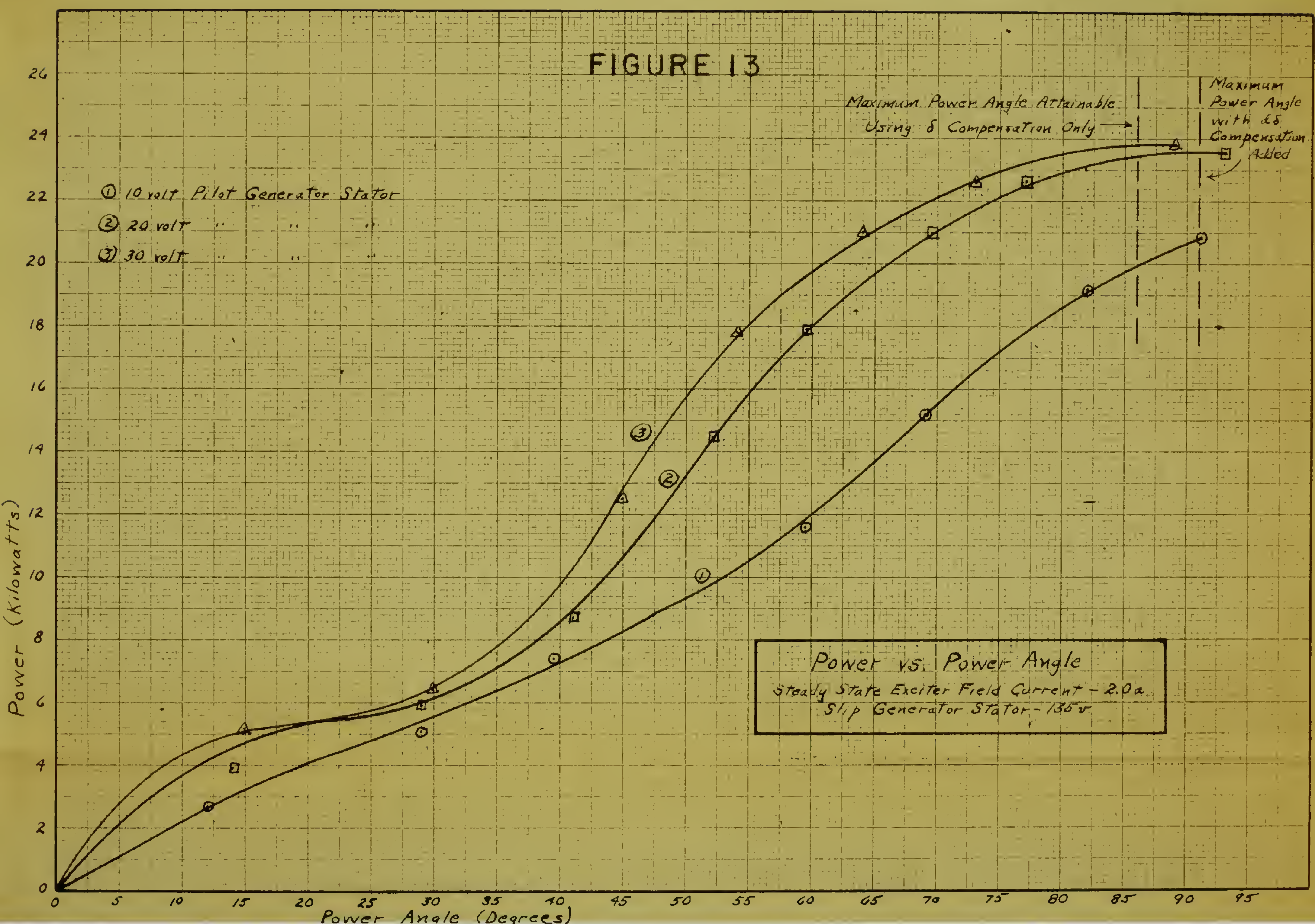


FIGURE 13
Maximum Power Angle Attainable Using δ Compensation Only
Maximum Power Angle with εδ Compensation Added
① 10 volt Pilot Generator Stator
② 20 volt " " "
③ 30 volt " " "
Power vs. Power Angle
Steady State Exciter Field Current - 2.0a
Slip Generator Stator - 135v
Power (Kilowatts)
Power Angle (Degrees)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

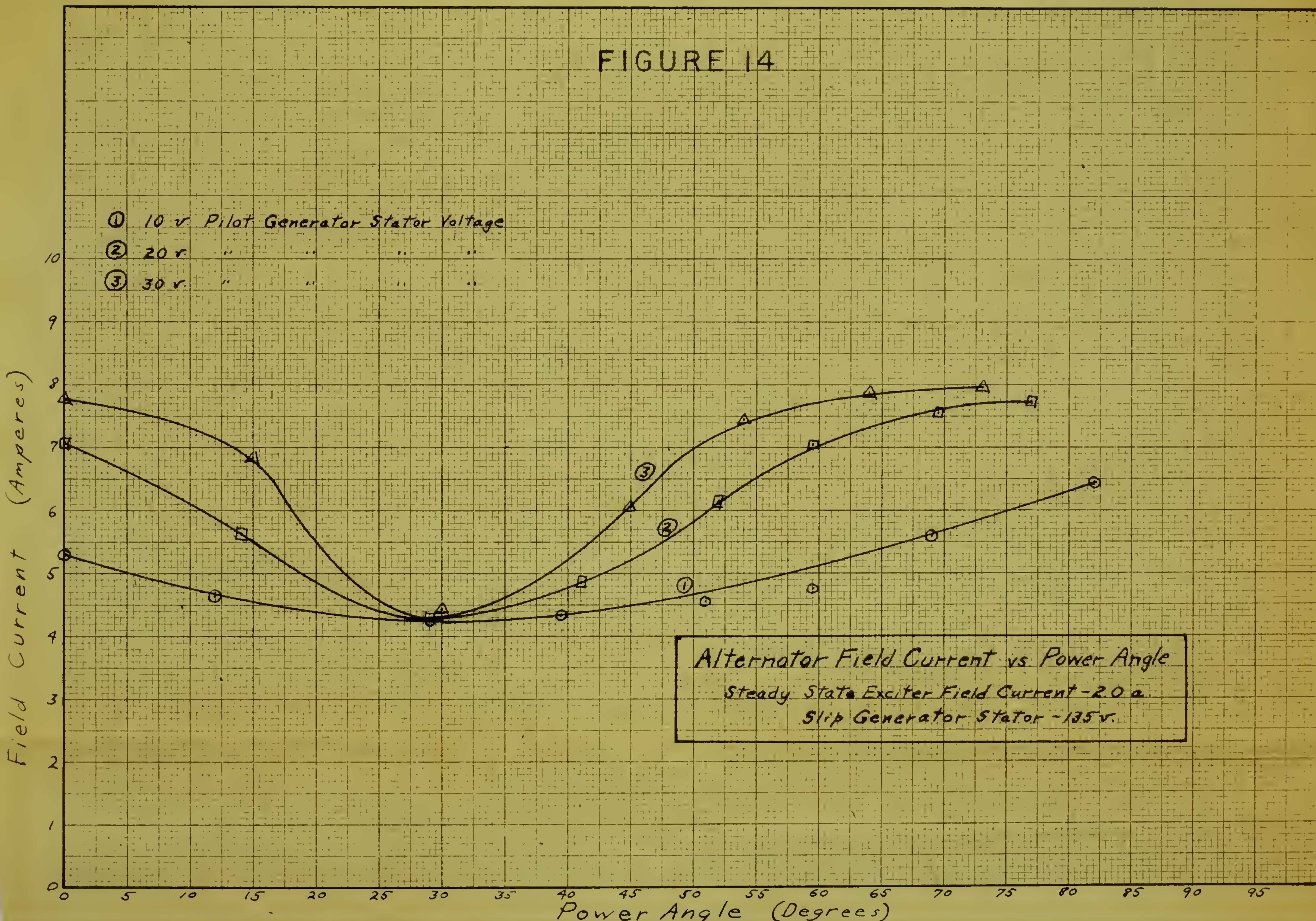


FIGURE 14
① 10 v. Pilot Generator Stator Voltage
② 20 v. " " " "
③ 30 v. " " " "
Alternator Field Current vs. Power Angle
Steady State Exciter Field Current - 2.0 a.
Slip Generator Stator - 135 v.
Field Current (Amperes)
Power Angle (Degrees)
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
①
②
③

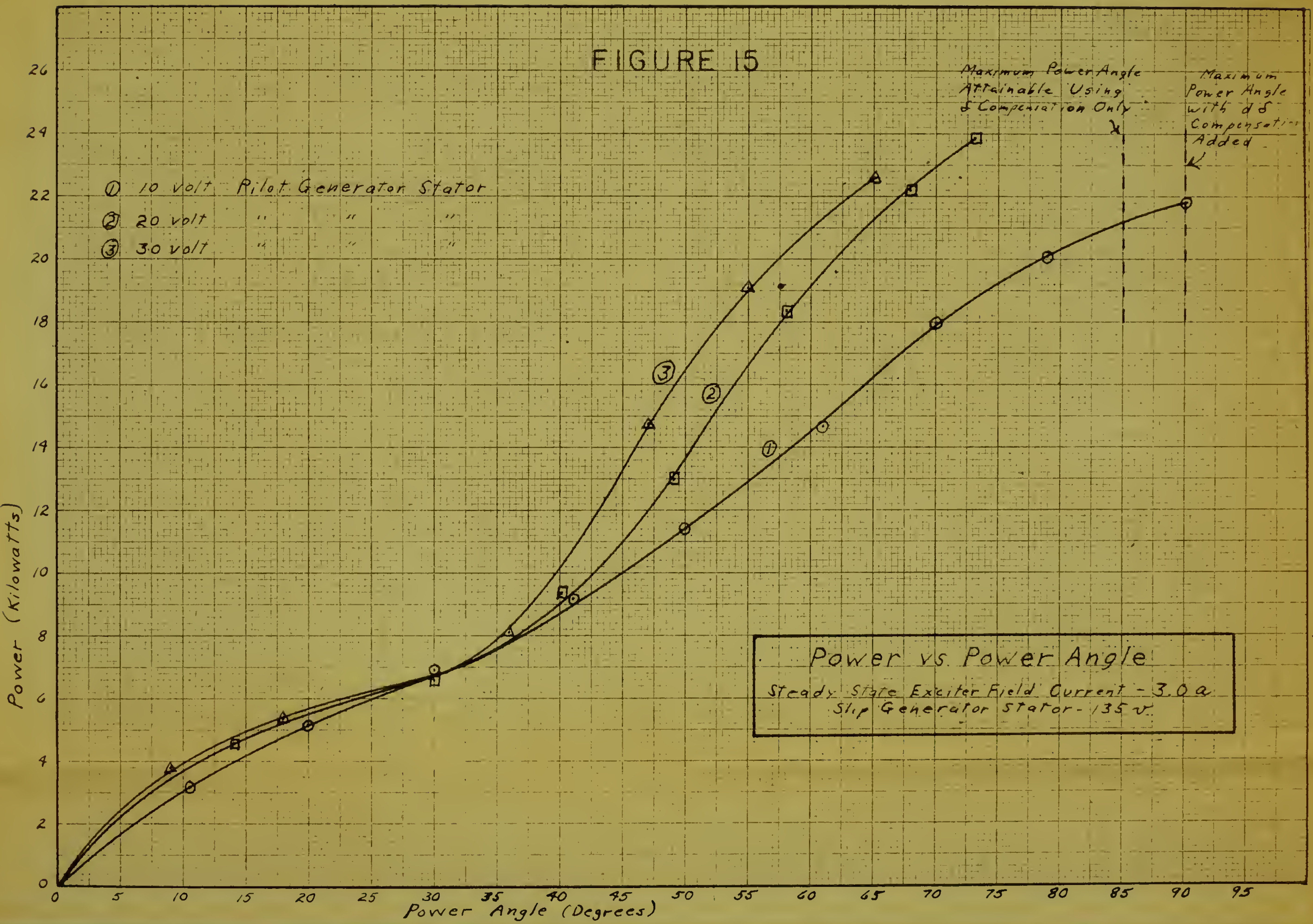
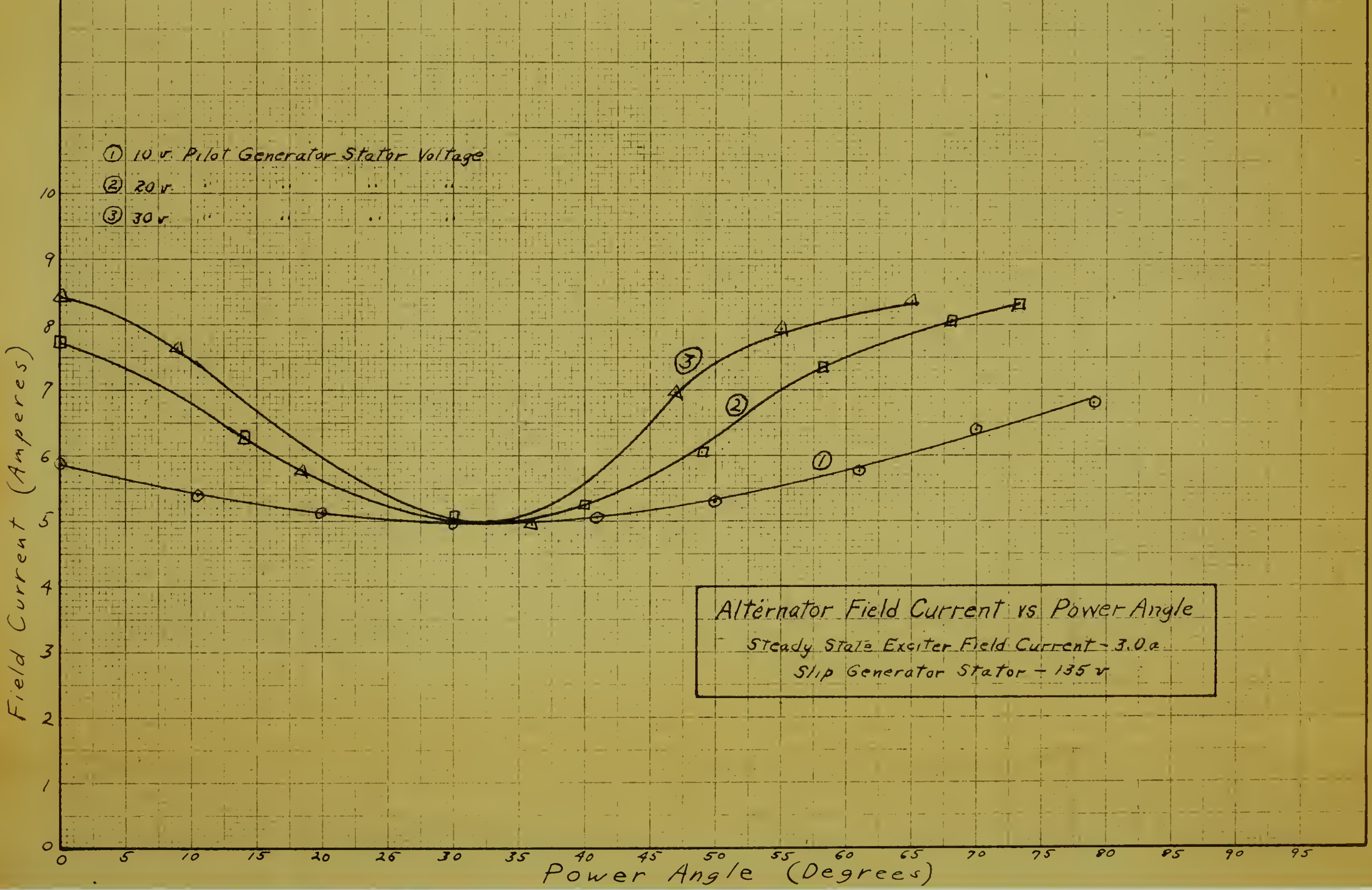


FIGURE 15
Maximum Power Angle Attainable Using δ Compensation Only
Maximum Power Angle with dδ Compensation Added
① 10 volt Pilot Generator Stator
② 20 volt " " "
③ 30 volt " " "
Power vs Power Angle
Steady State Exciter Field Current - 3.0 a
Slip Generator Stator - 135 v.
Power (Kilowatts)
Power Angle (Degrees)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

FIGURE 16



① 10 v. Pilot Generator Stator Voltage
② 20 v. " " " "
③ 30 v. " " " "
Alternator Field Current vs Power Angle
Steady State Exciter Field Current - 3.0 a
Slip Generator Stator - 135 v
Field Current (Amperes)
Power Angle (Degrees)
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

V DISCUSSION OF RESULTS

The curves of power vs. power angle show the effect on the range of stability of δ compensation (compensation proportional to power angle) and of both δ and $d\delta$ compensation (compensation proportional to rate of change of power angle). Whenever δ compensation is used, the curve of power vs. power angle rises with a steeper slope than on a similar curve with fixed excitation, because the component of field current proportional to δ increases with power angle. Thus the power curve of the alternator with δ compensation crosses a series of power curves with fixed excitation, as shown in Figure 17 below.

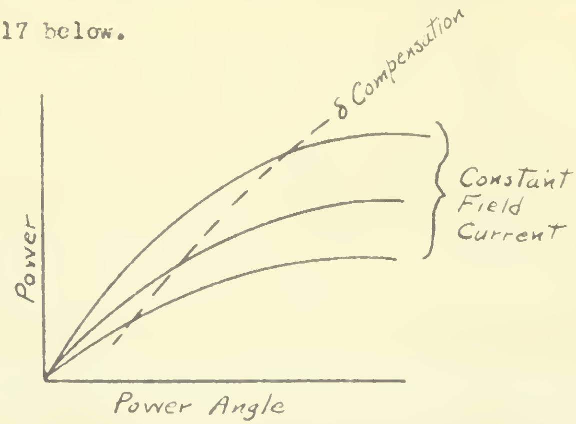


Figure 17.

The basic equation for the power generated by a salient pole alternator is

$$P = \frac{E_d V_t}{x_d} \sin\delta + \frac{V_t^{\,2}(x_d - x_q)}{2x_d x_q} \sin 2\delta$$

where P is power output at the terminals, E_d is excitation voltage due to the impressed field in the direct axis, V_t is terminal voltage,

x_d is direct-axis synchronous reactance, x_q is quadrature-axis synchronous reactance, and is power angle. Expressed in a different form,

$$P = V_t \left[\frac{E_d}{x_d} \sin \delta + \frac{V_t(x_d - x_q)}{2x_d x_q} \sin 2\delta \right] .$$

Since for the usual salient pole machine the value of x_q is only about seven-tenths that of x_d, the amplitude of the second harmonic is roughly one-quarter of the amplitude of the fundamental. Thus for operation against an infinite bus, making V_t a constant, the value of P at any desired power angle is determined primarily by the magnitude of E_d. With saturation effects absent in the alternator field, the excitation voltage E_d is almost directly proportional to field current or, algebraically, $E_d = K_d I_p$.

When automatic excitation is used, the alternator field current may be represented by the equation

$$I_f = I_{fo} + I_{f1} + I_{f2}$$

I_f is total alternator field current,

I_{fo} is steady-state or fixed component of field current,

I_{f1} is component of field current proportional to power angle,

I_{f2} is component of field current proportional to rate of change of power angle.

For any one run, I_{fo} is fixed by setting the exciter field current, exciter speed, and the alternator field rheostat position.

I_{f2} is zero except during changes in power angle due to changes in load and subsequent oscillations. Therefore, its effect is not evident in the curves of power vs. power angle, except the indirect effect of increasing the range of stability. With a properly aligned pilot generator rotor, the component I_{f1} could be made roughly proportional to power angle as has been heretofore assumed, but because the rotor was mechanically displaced about twenty-nine electrical degrees from the alternator rotor, I_{f1} is roughly proportional to the magnitude $\left|\delta - 29^\circ\right|$. This misalignment results in a total alternator field current which reaches a minimum at a power angle of 29°, sloping upward in both directions from that point. The rate at which I_f increases with power angle depends upon the magnitude of the proportionality factor K_1 in the following equation:

$$I_{f1} = K_1 \left|\delta - 29^\circ\right| .$$

A study of the curves of alternator field current in the Results section shows that K_1 is not a constant for any one run, due primarily to the saturation which occurs in the amplidyne as high voltages are placed across one of its control fields. Such a study also reveals, however, that in the range of power angle from about 30° to 60° the slope of the curve and hence the value of K_1 is determined by the magnitude of the pilot generator stator voltage. Increasing the stator voltage of the pilot generator causes a more rapid increase of alternator field current with increases in load.

The adverse effect of the 29° misalignment of the pilot generator rotor was accepted because it produced negative δ compensation only at very low power angles, where the alternator was inherently very stable. I_{f1} could be made proportional to rather than to $|\delta - 29°|$ by installation of a phase-shifting device between the pilot generator and the rectifier. Such a device would also enable one to set the position of zero δ compensation at any desired power angle. This would be desirable and perhaps mandatory in any practical installation.

To bring out the effects of automatic excitation shown in the power vs. power angle curves, it is necessary to assume definite sets of operating requirements. For purposes of illustration the following three operating conditions will be discussed: (1) continuously variable power requirements in the region between 30° and 80° power angle, with maximum power set by current rating of alternator; (2) high average power output of 17 kilowatts, with possible 5 kw. load increases; and (3) low average power output of 12 kilowatts, with possible 8 kw. load increases.

For condition (1), in which the operating region is established by upper and lower limits of power angle, maximum steady-state exciter field current is limited to 2.0 amperes because higher values cause the alternator to generate greater than rated currents before the maximum power angle is reached. Study of Figure 13, power vs. power angle for 2.0 amperes steady-state

exciter field current, shows that the higher (30 volt) stator voltage on the pilot generator produces about 600 watts more power at the upper limit of power angle. However, it will also be observed that at that upper limit the 30 volt curve is very flat, so that an additional 300 watts of power would be sufficient to drive the alternator out of synchronism. With only 20 volts on the pilot generator stator, the power output at the upper limit is only 2.5 per cent less while the additional power required to lose synchronism is 700 watts, or more than twice as much as that required with 30 volts on the stator. At the other extreme, use of only 10 volts on the pilot generator stator yields a power curve which is still rising sharply at a power angle of 80°, but with almost 5000 watts less power available at that limit. Of the combinations tested, therefore, 2.0 amperes steady-state exciter field current and a pilot generator stator voltage of 20 volts seems best for this set of operating requirements.

For condition (2), assume reasonably steady high power output with an average value of 17 kw., and possible 5 kw. variations from that average. A cursory study of Figures 3, 5, and 7 shows that a pilot generator stator voltage less than 20 volts and steady state exciter field currents less than 2.0 amperes will not produce power up to 22 kw. without loss of synchronism. Further study of Figures 5 and 7 indicates that the maximum power requirement of 22 kw. can

be reached at a lower power angle, and hence with less danger of exceeding the stability limit, by the use of 3.0 amperes steady-state field current in the exciter. Furthermore, this can be done without exceeding the current rating of the alternator. Finally, from Figure 15, we note that there is very little choice between the use of 20 and 30 volts on the pilot generator stator. Use of the higher stator voltage produces 22 kw. active power at a slightly lower power angle, but from the slopes of the two curves at the 22 kw. level it is evident that approximately the same additional increment of power will cause loss of synchronism at either stator voltage. Since the 30 volt curve approaches the alternator current rating very closely at the 22 kw. point, it would probably be best to use the combination of 3.0 amperes steady-state exciter field current and a pilot generator stator voltage of 20 volts for these operating requirements.

Any possible effect of large variations in power requirement is given by condition (3), which assumes an average power output of 12 kw. with possible 8 kw. variations from the average. Figures 3, 5, and 7 show first that a steady-state exciter field current of 1.0 ampere is insufficient to give the maximum power requirement. Any other combination shown on the curves could be used except a 1.5 ampere steady-state exciter field current and 10 volt pilot generator stator voltage. At the upper power limit there is little to choose from the various combinations, although

higher values yield 20 kw. at power angles farther from the stability limit. At the lower power limit of 4 kw., with the 29° rotor offset employed in these tests, there is again little to choose from among the combinations tested. Near the average power of 12 kw. the slope of the power vs. power angle curve is greatest with maximum value of both parameters, so a 30 volt pilot generator stator voltage and 3.0 amperes steady-state exciter field current is probably desirable.

For all curves of power vs. power angle, the power was connected to a terminal voltage of 115 volts. This was considered necessary in order to simulate operation of the generator against an infinite bus. Actually, the terminal voltage increased with line current due to the voltage drops in the primary and secondary windings of the transformers. In each run of Test 4, the voltage regulator output to the rectifier was held constant manually in order to eliminate this effect on the compensation. The power correction was derived as follows:

$$P = V_t \left[\frac{E_d}{x_d} \sin\delta + \frac{V_t(x_d - x_q)}{2x_d x_q} \sin 2\delta \right]$$

It was assumed that the error in the term $\frac{V_t(x_d - x_q)}{2x_d x_q} \sin 2\delta$ due to error in V_t is negligible with respect to P. Therefore, P was considered directly proportional to V_t for any given E_d and δ.

The oscillation of the power angle at an apparently constant load with no compensation was in all probability due to line fluctuations in both the a-c line and the d-c line feeding the driving motor. This fluctuation, coupled with the large inertia of the rotors of the machines, made these oscillations troublesome, particularly at large power angles. The oscillation was greater when δ compensation was used. In this case the δ compensation bucked the change in power angle resulting from the line fluctuations and then overshot the correct power angle for the particular load, with a resultant large amplitude oscillation. However, when $d\dot{\delta}$ compensation was added, the output of the slip generator acted as a damping force and rapidly damped out any oscillations. For any given power angle, minimum oscillation was observed when $d\delta$ compensation was used in conjunction with the δ compensation. As the magnitude of the slip generator stator voltage was decreased, thereby decreasing the $d\delta$ compensation, the oscillation became greater and took longer to damp out. Therefore, for this particular case it was best to use maximum $d\delta$ compensation (135 volts on the slip generator stator).

Since small fluctuations in line voltage and in the speed of the prime mover would be almost certain in any practical installation, it is considered essential that both δ and $d\delta$ compensation be used if the range of stability is to be increased by any measurable amount.

Although no tests for transient stability were made with this system, it is believed that use of combined δ and $d\delta$ compensation would again increase the range of stability of the alternator. To test the transient stability, it would be necessary to introduce a model transmission line or a group of series inductors between the alternator and the infinite bus, so sudden loads could be applied or removed by simple switching arrangements. Even with this change in the apparatus, an artificial situation would still be present because the speed of the prime mover is locked by the line frequency as long as the alternator is connected to the a-c supply.

The type of automatic excitation demonstrated in this system is superior to the usual voltage-regulated automatic excitation for alternators which must operate at high power angles. When stability limitations are important, as they are in most installations, but particularly in cases where long transmission lines are involved, the use of automatic excitation dependent upon power angle is obviously a more positive control than that dependent upon a secondary factor like terminal voltage. Voltage-regulated excitation increases the range of stability of the alternator only insofar as the terminal voltage tends to decrease with increasing load and hence with increasing power angle. Logic would seem to point out the advantage of using the criterion of stability, power angle, as the basis of the automatic excitation system. Our tests

bear out the validity of this statement, for even with the relatively crude apparatus employed, it was possible to operate at power angles well beyond the fixed-excitation limit.

Both Dahl (7) and Frey (1) mention the possibility of operating a synchronous machine on the back side of the power vs. power angle curve; i.e., at angles greater than that for maximum power through use of high speed regulation. Dahl refers only to alternators with voltage-regulated excitation, but Frey outlines in theoretical terms how it is possible to operate a non-salient pole synchronous machine at power angles greater than 90° by the use of automatic excitation proportional to power angle. Analysis of the power equation for salient-pole alternators shows that with constant excitation the power will peak at a power angle less than 80°, indicating that by use of δ and $d\delta$ compensation we have succeeded in maintaining such a machine dynamically stable on the back side of the power vs. power angle curve. However, it must be noted that synchronous operation could not be maintained at power angles much beyond the maximum obtained with fixed excitation, possibly because of the undesirable combination of large time lags in the exciter and the saturation of the amplidyne at relatively low pilot generator stator voltages.

It is realized that a great deal of work remains to be done in the field of automatic excitation proportional to power angle

before such an installation might be commercially feasible. However, the data presented in this thesis indicates the possibilities such a system offers in extending the range of stability of any alternator, since it seems logical to assume that the maximum power angle attainable could be increased at least 10° for either a salient-pole or a cylindrical machine. Further research should be carried on, eliminating the undesirable features of our design as mentioned in the previous paragraph. Use of a properly designed two-field exciter and an amplidyne or electronic amplifier which would not saturate at the field currents required might extend the range of stability much farther than was done in this thesis. More stable operation at high power angles might also result from the use of a phase-shifting device in the δ compensation circuit which would shift the zero point of δ compensation to any desired power angle.

VI CONCLUSIONS

From the observations and discussion it is concluded that:

1. The range of stability of this particular salient-pole synchronous generator was increased by about five degrees when compensation proportional to power angle was used, and by about ten degrees when compensation proportional to both power angle and rate of change of power angle was used.

2. Compensation proportional to rate of change of power angle is necessary when compensation proportional to power angle is used, in order to damp out the oscillations set up in the system.

3. Choice of proportionality factors between the compensating component of field current and power angle is dependent upon the range of power angles in which it is desired to operate the machine.

4. It is feasible to operate a synchronous machine using this excitation system at power angles greater than that at which maximum power occurs for any given fixed field current.

VII RECOMMENDATIONS

1. Further studies of this system are recommended with emphasis on operation at power angles greater than ninety degrees using a larger amplidyne and an exciter more suited to the power requirements.

2. An investigation of the operation of this system with the generator driving a synchronous motor would be desirable.

3. It is recommended that a phase shift device be placed between the voltage regulator and the rectifier in order to vary the power angle at which the pilot generator voltage and the regulator voltage are in phase.

VIII APPENDIX

A. SUPPLEMENTARY INTRODUCTION

The basic method of obtaining components of main generator field current proportional to power angle and rate of change of power angle is simple, as outlined in the introduction. Setting up a working model of the equipment in an electrical machinery laboratory, however, involves many problems. The following practical problems and their solutions should be studied by anyone interested in further research or development work on automatic excitation of alternators.

There was a pilot generator already mounted on the same shaft as the alternator selected for test, but no wound rotor induction motor was available in the laboratory. The motor was to be used not for power, but merely to provide a voltage at the slip rings proportional to rate of change of power angle. Hence, a cage type induction motor was rebuilt as a wound rotor type with very fine wire in the rotor windings to give the maximum number of turns and the highest possible induced voltage.

Combining the amplidyne output and the steady-state component of the generator field required a two-field exciter. Since none was available in the laboratory, it was necessary to convert a six-pole direct-current generator to a two-field generator. This was accomplished by disconnecting the field windings on each pole and connecting two opposite poles to provide one field and another pair of opposite poles for the other field. Two pairs of brushes were

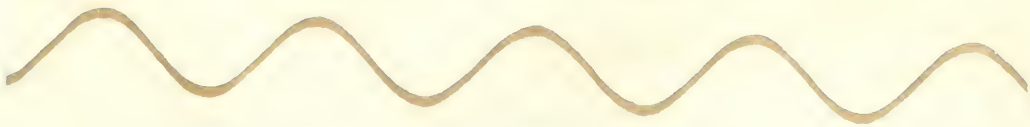
removed, leaving only one pair. A great deal of apprehension arose as to the amount of ripple that might be present in the output, so an oscillogram was taken of the output voltage at load with both fields excited. This oscillogram showed no discernable ripple at all. Even though the size of the generator was large for the output required, we considered our exciter problem solved.

Little difficulty was encountered in providing a voltage proportional to power angle. Magnitude of the pilot-generator stator voltage was controlled by a field rheostat, and that of the reference voltage by a three-phase variac placed across the line. The vector difference was then placed across two terminals of a selenium rectifier bridge, the output of which was applied to one field of the amplidyne.

Rewinding a cage-type motor as a wound-rotor type provided a voltage signal proportional to rate of change of power angle, but the signal was small and almost hidden by a ripple voltage due to slot noise. Analysis of an oscillogram of the ripple voltage (Fig. 18) showed it to consist of a 120 cycle fundamental with a strong third harmonic. A simple low-pass R-C filter was used to eliminate this undesirable ripple voltage, presenting at the filter output an infinitesimal voltage except during periods of varying load; i.e., varying power angle. However, even with sudden changes of load, the huge inertia of the rotating machines produced a relatively slow change

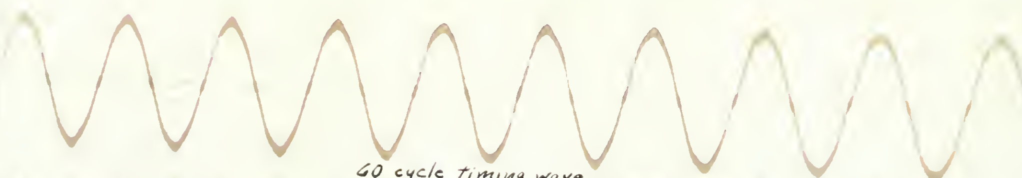
in power angle and hence a small voltage (maximum of one volt) at the filter output terminals. A General Radio Type 715-A direct current amplifier was required to increase the voltage to a usable value, and an output stage consisting of two 6L6 tubes connected as a d.c. bridge type amplifier was used for current amplification and impedance matching. This combination of amplifiers provided control field current up to 15 milliamperes for the high-impedance amplidyne field. A schematic diagram of the compensation system is shown in Figure 19.

At first an attempt was made to operate the synchronous generator at its rated voltage, feeding its output into the 230-volt three-phase line in the laboratory. It was found that for all but very small field currents, the increase in power angle was limited by the current rating long before it was limited by stability. For this reason it was decided to operate the machine at half its rated voltage by feeding the output through auto-transformers into the 230-volt line. This resulted in the terminal voltage of the machine rising as the current output increased. It would have been much better to have operated at a constant terminal voltage, but because of the laboratory limitations, it was necessary to accept the varying voltage.

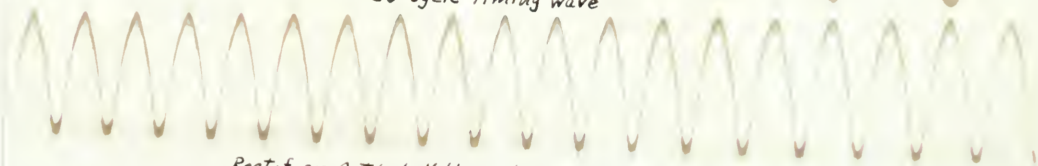


60 cycle timing wave

Slip Generator Output Voltage



60 cycle timing wave



Rectifier Output Voltage during change of load

FIGURE 18

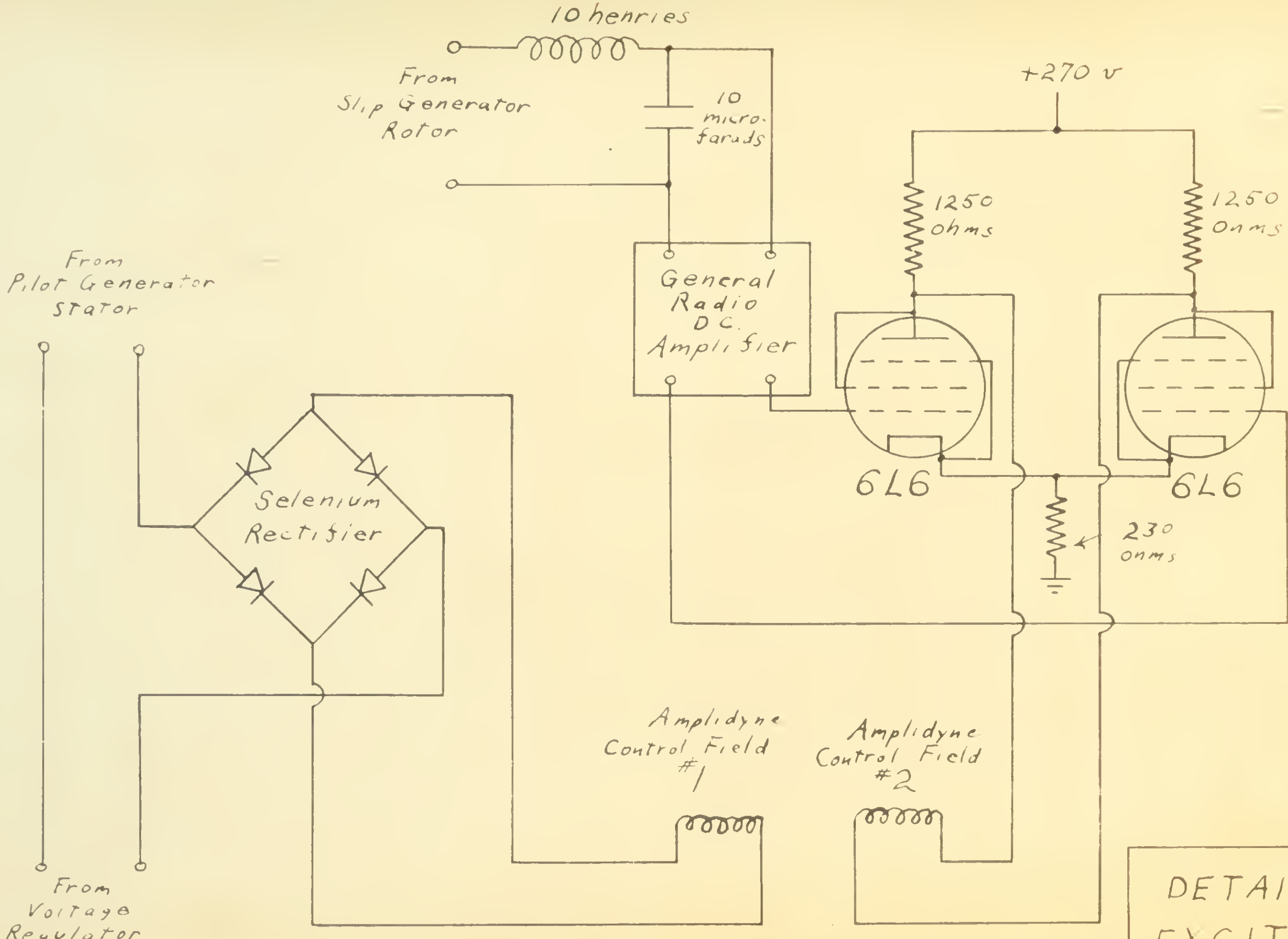


FIGURE 19

DETAILS OF
EXCITATION
CONTROL

B. EQUIPMENT

Synchronous Generator (M. I. T. Lab. No. 804A)

Westinghouse 3-phase, 60 cycle, 1200 rpm, generator.

44kva., 230 volts, 110 amps., 80 per cent P. F.

Excitation amps. 15, volts 125.

Pilot Generator (M. I. T. Lab. No. 804B)

Westinghouse 3-phase, 60 cycle, 1200 rpm. generator.

2 kva., 230 volts, 5 amps., 80 per cent P. F.

Slip Generator

3-phase, 60 cycle, 1200 rpm., wound rotor induction

motor rebuilt by Electrical Shop of Boston Naval Shipyard.

Rated stator voltage 230 volts.

Exciter (M. I. T. Lab. No. 59B)

Electro-Dynamic direct-current generator, shunt-wound.

10 hp., 230 volts, 39 amps., 425-1275 rpm.

Amplidyne (M. I. T. Lab. No. 1301)

General Electric amplidyne generator, Model 5AM48P1

Input 115 volts, 1-phase, 60 cycle, 6 amps., 1725 rpm.

Output 200 watts, 100 volts, 2.0 amps.

Amplifier (M. I. T. Lab. No. 186)

General Radio direct-current amplifier.

Type 715-A, Serial 186.

C. ORIGINAL DATA

List of symbols used:

Main Generator

I_f Field current in amperes. Subscript o denotes steady-state component

V_f Voltage applied to field in volts.

ϕ Phase angle meter reading in degrees.

P Power output in kilowatts.

I_L Current output ÷ 40 in amperes.

V_L Terminal voltage in volts

Compensating System

V_{ac} A.C. voltage on rectifier in volts.

V_{dc} D. C. output of rectifier in volts which is the voltage applied to the No. 1 amplidyne control field.

I'_{f1} No. 1 amplidyne control field current in milliamperes.

V_{st} Stator voltage of pilot generator in volts.

V Three-phase variac output to rectifier in volts.

Exciter

I_{f1} Steady state exciter field current in amperes.

I_{f2} Compensating exciter field current in amperes which is the output current of the amplidyne.

V_o Exciter output in volts.

TEST I: No automatic excitation.

Run I	I_f	ϕ	P	I_L	V_L
	3.6	29.0	0	0	112.0
	3.6	3.0	4.4	0.58	115.5
	3.6	-29.0	8.8	1.33	117.0
	3.6	-39.0	9.6	1.55	116.0

Run 2					
	4.2	29.0	0	0	111.0
	4.2	7.0	4.2	0.50	115.5
	4.2	-10.0	7.7	0.97	116.5
	4.2	-31.0	10.7	1.45	118.0
	4.2	-42.0	11.9	1.77	115.5
	4.2	-55.0	12.3	1.97	115.5

Run 3					
	4.6	29.0	0	0.20	113.0
	4.6	8.0	4.2	0.57	116.0
	4.6	-5.0	7.8	0.96	117.5
	4.6	-25.0	11.3	1.45	117.0
	4.6	-37.0	12.6	1.77	117.5
	4.6	-56.0	13.5	2.12	117.5

Run 4					
	5.0	29.0	0	0.50	114.0
	5.0	12.0	4.0	0.61	116.5
	5.0	1.0	6.9	0.88	118.0
	5.0	-17.0	11.5	1.35	120.5
	5.0	-36.0	13.5	1.80	118.0
	5.0	-48.0	14.6	2.11	118.0

TEST I (continued)

Run 5	I_f	ϕ	p	I_L	V_L
	5.5	29.0	0	0.62	115.5
	5.5	15.0	4.0	0.75	117.5
	5.5	0.0	8.2	1.05	118.5
	5.5	-15.0	12.0	1.45	121.0
	5.5	-30.0	14.4	1.80	121.0
	5.5	-46.0	16.2	2.18	119.0

Run 6	6.0	29.0	0	0.86	115.0
	6.0	14.0	4.3	0.91	118.0
	6.0	0.0	8.9	1.17	121.0
	6.0	-13.0	12.3	1.49	121.5
	6.0	-30.0	15.9	1.90	122.0
	6.0	-42.0	17.5	2.22	120.5
	6.0	-50.0	18.3	2.42	119.5

Run 7	6.5	29.0	0	1.06	115.0
	6.5	14.0	5.1	1.11	120.5
	6.5	0.0	9.9	1.34	122.5
	6.5	-13.0	14.5	1.65	123.5
	6.5	-25.0	16.8	2.03	123.5
	6.5	-41.0	19.1	2.30	123.0

Run 8	7.0	29.0	0	1.24	116.5
	7.0	16.0	4.8	1.26	119.5
	7.0	1.0	10.3	1.50	122.0
	7.0	-13.0	14.8	1.86	122.0
	7.0	-30.0	19.3	2.32	124.0
	7.0	-40.0	20.8	2.53	122.5
	7.0	-50.0	21.6	2.73	121.5

(continued)

Run 9	I_f	ϕ	P	I_L	V_L
	7.5	29.0	0	1.42	116.0
	7.5	13.0	6.3	1.49	120.0
	7.5	1.0	11.3	1.64	123.5
	7.5	-11.0	15.1	1.86	125.5
	7.5	-21.0	18.4	2.17	126.0
	7.5	-32.0	20.9	2.47	124.5

TEST . Automatic Excitation using δ compensation only.

	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run I	6.4[illegible]	41.0	30.0	0	1.19	116.0	14.5	10.4	9.0	27.5	28.0	2.33	2.25	153
	5.16	37.0	16.0	4.5	0.98	118.5	[illegible].0	5.8	5.0	27.5	29.0	2.33	1.53	138
	4.40	26.0	2.0	[illegible].5	0.71	116.0	0	1.5	1.2	27.5	28.5	2.33	0.60	10[illegible]
	4.95	30.0	-12.0	9.2	1.12	119.0	2.0	2.9	2.5	27.1	29.2	2.33	0.80	112
	6.30	33.0	-21.0	14.7	1.76	121.5	10.0	6.7	5.5	27.1	29.7	2.33	1.65	140
	6.65	41.0	-29.0	17.9	2.10	122.5	14.0	10.7	8.6	27.0	30.0	2.33	2.18	150
	6.90	42.5	-30.0	21.9	2.75	122.5	24.0	17.4	15.0	27.8	30.0	2.33	2.70	157
Run 2	5.52	32.5	29.0	0	0.67	113.0	14.0	10.0	8.5	27.3	28.0	0.97	2.20	124.0
	4.75	27.8	15.0	3.1	0.55	114.0	7.0	4.7	4.0	27.3	28.2	1.00	1.40	106.0
	2.76	16.2	0.0	3.5	0.64	112.0	0.0	0.3	0.5	27.3	27.8	1.00	0.30	63.0
	4.40	26.8	-10.0	9.0	1.16	115.5	5.0	4.3	3.7	27.3	28.7	1.00	1.24	100.0
	5.40	32.0	-31.0	14.0	1.76	118.0	14.0	9.9	8.3	26.8	29.3	1.00	2.13	121.5
	5.30	34.0	-42.0	16.3	2.10	117.0	17.0	14.0	13.5	27.0	29.5	1.00	2.50	127.0
Run 3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TEST 2: Automatic Excitation using δ compensation only. (cont.)

	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run 4	6.60	39.4	29.0	0.0	1.12	113.0	9.5	6.1	4.8	20.0	19.6	2.96	1.50	148.0
	5.28	31.7	15.0	3.7	0.71	113.0	6.0	2.5	1.9	20.0	19.7	2.93	0.67	121.0
	4.38	26.2	0	6.1	0.75	114.0	0.0	0.0	0.0	20.0	19.8	2.93	0.20	99.0
	4.94	28.8	-16.0	10.1	1.29	117.0	5.0	2.1	1.5	19.9	20.2	2.93	0.55	110.5
	6.00	35.6	-25.0	15.1	1.82	119.0	8.0	4.4	3.5	20.0	20.6	2.93	1.15	135.0
	6.87	41.2	-35.0	19.6	2.37	122.5	10.8	7.4	6.0	20.0	21.0	2.93	1.75	154.0
	7.22	43.0	-45.0	22.1	2.69	122.0	14.0	9.9	8.0	20.0	21.0	2.93	2.12	161.0
Run 5	6.37	38.2	29.0	0.0	1.01	114.0	9.5	6.1	4.8	20.0	19.7	2.38	1.50	143.0
	5.04	29.8	14.0	3.9	0.61	114.0	6.0	2.5	1.8	20.0	19.9	2.36	0.70	114.0
	4.07	24.7	0	5.0	0.63	114.0	0.0	0.0	0.0	20.0	19.9	2.38	0.20	93.0
	4.61	28.1	-15.0	9.2	1.19	116.5	5.3	2.0	1.6	20.0	20.1	2.36	0.58	106.0
	5.85	35.4	-25.0	14.5	1.74	120.0	8.2	4.6	3.6	20.0	20.7	2.38	1.20	132.0
	6.61	39.8	-36.0	18.7	2.24	122.0	11.3	7.8	6.1	19.8	20.8	2.38	1.80	148.0
	6.97	42.0	-46.0	21.3	2.66	122.0	14.5	10.5	8.5	20.0	20.8	2.38	2.20	156.0
	7.10	42.9	-53.0	22.2	2.95	121.0	17.0	12.4	10.0	20.0	20.8	2.38	2.35	159.0
Run 6	4.80	29.0	29.0	0.0	0.41	112.0	9.5	6.1	4.8	20.0	19.2	0.97	1.50	108.5
	2.88	18.7	8.0	2.2	0.46	110.0	4.0	1.4	1.2	20.0	19.1	0.97	1.40	68.0
	2.78	16.4	-10.0	4.1	0.77	112.0	2.5	0.8	0.7	20.0	19.3	0.97	0.35	65.0
	3.82	23.6	-21.0	8.2	1.14	114.0	7.0	3.4	2.6	20.0	19.6	0.97	0.93	88.0
	4.82	29.5	-32.0	12.1	1.56	117.5	9.7	6.3	4.9	20.0	20.2	0.97	1.36	109.0
	5.24	31.6	-45.0	15.1	2.00	119.0	13.5	9.4	7.5	20.0	20.3	0.97	2.03	119.0
	5.52	33.0	-55.0	16.5	2.42	118.0	17.0	12.5	9.8	20.1	20.3	0.97	2.30	127.0

TEST [illegible]: Automatic Excitation using δ compensation only (cont.)

	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run 7	3.27	20.1	29.0	0.0	0.0	113.5	4.5	2.2	1.7	10.0	9.5	0.97	0.65	76.0
	2.88	16.7	15.0	1.6	0.30	114.0	2.7	0.7	0.6	10.0	9.5	0.97	0.34	65.0
	2.58	15.3	-2.0	3.2	0.67	115.0	0.9	0.5	0.1	10.0	9.7	0.97	0.21	59.5
	2.70	15.9	-16.0	4.7	0.88	115.0	2.1	0.65	0.4	10.0	9.7	0.97	0.28	62.0
	2.97	17.7	-26.0	6.6	1.12	116.0	2.5	1.5	1.1	10.0	9.8	0.97	0.45	68.5
	3.61	21.2	-36.0	9.3	1.40	117.5	5.1	2.6	2.0	10.0	9.9	0.97	0.76	81.0
	4.15	24.5	-45.0	11.8	1.76	118.0	6.5	3.6	2.9	10.0	10.0	0.97	1.05	93.0
	4.57	26.7	-55.0	13.6	2.07	119.0	8.0	4.8	3.7	10.0	10.0	0.97	1.34	102.0
Run 8	5.02	29.0	29.0	0.0	0.32	115.0	4.5	2.0	1.6	10.0	9.7	2.38	0.64	111.5
	4.80	26.0	15.0	3.0	0.33	117.0	2.6	0.9	0.6	10.0	9.8	2.33	0.35	98.0
	4.20	24.6	0.0	5.9	0.71	118.0	1.0	0.3	0.1	10.0	10.0	2.33	0.25	94.5
	4.24	25.6	-16.0	8.4	1.07	119.0	2.4	0.8	0.5	10.0	10.1	2.33	0.33	96.0
	4.48	27.0	-26.0	10.7	1.35	120.0	3.7	1.7	1.2	10.0	10.1	2.33	0.50	102.0
	5.00	30.0	-36.0	13.5	1.73	121.0	5.1	2.7	2.0	10.0	10.2	2.33	0.75	112.0
	5.42	32.0	-45.0	16.2	2.14	120.5	6.3	3.5	2.8	10.0	10.2	2.33	1.00	120.0
	6.02	34.9	-55.0	18.1	2.57	121.5	8.0	5.0	3.7	10.0	10.2	2.33	1.8	
Run 9	4.98	29.8	29.0	0.0	0.40	115.0	4.4	2.1	1.5	10.0	9.7	2.96	0.59	112.0
	4.60	27.2	14.0	3.7	0.48	117.0	2.5	0.7	0.5	10.0	9.8	2.83	0.31	103.0
	4.42	26.6	0.0	5.6	0.67	118.0	1.0	0.3	0.1	10.0	9.9	2.83	0.23	99.0
	4.47	27.2	-15.0	8.7	1.00	119.0	2.1	0.70	0.5	10.0	10.0	2.83	0.30	101.0
	4.[illegible]	27.9	-25.0	10.9	1.36	119.5	3.5	1.5	1.0	10.1	10.1	2.83	0.43	105.0
	5.15	30.4	-36.0	14.1	1.82	121.0	4.9	2.6	1.9	10.1	10.1	2.83	0.71	115.0
	5.64	32.6	-44.0	16.4	2.16	122.0	6.2	3.4	2.6	10.1	10.2	2.83	0.98	128.0
	6.25	37.[illegible]	-57.0	19.6	2.67	121.0	8.0	5.2	4.0	10.0	10.2	2.83	1.40	142.0

TEST 3: Automatic Excitation using δ and $d\delta$ compensation with 135~ on stator of slip generator.

Run 1	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	4.74	29.2	29.0	0.0	0.25	110.0	4.6	2.3	1.8	10.0	9.7	2.38	0.41	105.0
	4.14	24.8	14.0	2.7	0.18	113.0	2.5	0.9	0.8	10.0	9.8	2.38	0.13	92.0
	3.85	23.3	0.0	4.8	0.61	114.0	1.0	0.35	0.1	10.0	10.0	2.38	0.0	86.0
	3.94	24.2	-14.0	7.8	1.01	115.0	2.0	0.56	0.4	10.0	10.1	2.38	0.09	88.5
	5.24	31.5	-28.0	13.1	1.62	119.0	4.2	1.80	1.4	10.0	10.3	2.38	0.70	115.5
	5.45	32.3	-38.0	15.0	1.89	120.0	5.5	2.95	2.3	10.0	10.4	2.38	0.74	119.0
	5.98	35.6	-50.0	18.4	2.44	121.0	7.4	4.30	3.4	10.0	10.6	2.38	1.07	131.5
	6.25	38.3	-57.0	19.8	2.69	122.0	8.2	5.30	4.1	10.0	10.7	2.38	1.26	138.0

Run 2	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	5.13	30.7	29.0	0.0	0.50	114.0	4.6	2.2	1.7	10.0	9.8	2.96	0.50	113.0
	4.65	27.3	14.0	3.2	0.44	116.0	2.9	1.1	0.7	10.0	10.0	2.96	0.17	101.5
	4.40	26.7	0.0	5.8	0.73	116.0	1.5	0.4	0.2	10.0	10.1	2.96	0.10	98.0
	4.58	27.7	-14.0	8.3	1.04	117.0	2.3	0.7	0.5	10.0	10.2	2.96	0.20	101.0
	4.95	30.2	-30.0	12.3	1.57	119.0	4.5	2.2	1.6	10.0	10.3	2.96	0.45	110.0
	5.75	35.2	-40.0	16.4	2.09	120.0	6.0	3.2	2.6	10.0	10.6	2.96	0.83	120.5
	6.04	37.1	-47.0	18.4	2.43	120.0	6.9	4.1	3.1	10.0	10.6	2.96	1.02	134.0
	6.38	40.5	-56.0	20.7	2.77	121.0	8.2	5.1	4.1	10.0	10.6	2.96	1.33	147.0

Run 3	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	3.15	19.0	29.0	0.0	0.04	112.0	4.5	1.8	1.4	10.0	9.3	0.98	0.50	72.0
	[illegible]	16.3	15.0	1.4	0.38	112.0	2.3	0.7	0.5	10.0	9.3	0.98	0.35	60.0
	2.47	14.6	0.0	3.1	0.72	113.0	0.5	0.2	0.1	10.0	9.3	0.98	0.12	55.0
	[illegible]	[illegible]	-15.0	4.5	[illegible]	113.0	1.5	0.5	0.3	10.0	[illegible]	0.98	0.19	57.5
	[illegible]	[illegible]	-30.0	7.9	1.20	114.5	4.2	1.9	1.5	10.0	9.6	0.98	0.58	72.5
	[illegible]	23.1	-40.0	10.0	1.62	117.0	5.7	3.0	2.5	10.0	9.7	0.98	0.90	86.0
	4.56	20.2	-50.0	[illegible]	2.07	117.5	7.1	4.1	3.5	10.0	9.8	0.98	1.20	100.0
	4.92	[illegible]	-59.0	14.5	2.35	[illegible]	8.4	5.2	4.3	10.0	9.9	[illegible]	1.40	[illegible]

TEST 3 (cont.)

Run	I_f	V_f	ϕ	F	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run 4	4.96	28.8	29.0	0.0	0.37	112.5	9.1	5.5	4.5	19.7	19.8	0.98	1.42	108.5
	3.48	20.9	14.0	2.0	0.10	113.0	5.0	1.9	1.5	19.7	19.9	0.98	0.60	74.0
	2.53	17.2	0.0	2.9	0.68	117.5	0.0	0.1	0.1	19.8	19.9	0.98	0.12	57.0
	3.55	21.3	-15.0	6.7	0.96	116.0	5.5	2.4	2.0	19.9	20.2	0.98	0.69	78.0
	5.08	30.0	-30.0	12.9	1.61	120.0	9.5	6.2	5.1	19.7	21.0	0.98	1.57	112.0
	5.58	32.7	-40.0	15.9	2.04	120.0	12.7	9.2	7.7	19.7	21.1	0.98	2.05	122.0
	5.85	34.1	-50.0	17.4	2.36	120.0	16.0	11.4	9.5	19.7	21.1	0.98	2.40	127.5
Run 5	6.65	39.6	29.0	0.0	1.10	115.0	9.1	5.9	4.8	19.7	19.8	2.38	1.50	145.0
	5.20	31.7	15.0	3.3	0.61	116.0	5.3	2.5	2.0	19.7	20.0	2.38	0.75	117.0
	4.22	25.3	0.0	5.3	0.65	116.0	0.0	0.1	0.0	19.7	20.2	2.38	0.19	92.0
	4.79	28.7	-16.0	10.0	1.22	18.5	5.6	2.6	2.1	19.7	20.7	2.38	0.60	107.0
	6.28	36.9	-27.0	16.1	1.91	122.5	8.8	5.5	4.5	19.7	21.3	2.38	1.36	136.0
	7.00	41.7	-38.0	21.0	2.49	124.0	12.0	8.6	7.1	19.7	21.6	2.38	1.96	152.0
	7.37	43.4	-48.0	22.4	2.94	123.0	14.9	11.2	9.3	19.7	21.5	2.38	2.25	159.0
Run 6	6.90	41.1	29.0	0.0	1.10	116.0	9.1	5.8	4.5	19.5	20.2	2.96	1.40	145.5
	5.27	31.0	13.0	4.0	0.63	117.0	4.5	2.0	1.5	19.5	20.4	2.96	0.5[illegible]	115.0
	4.23	26.7	0.0	6.2	0.75	117.0	0.0	0.2	0.1	19.5	20.5	2.96	0.14	97.0
	5.19	31.7	-15.0	10.8	1.30	121.5	5.3	2.6	2.0	19.7	21.1	2.96	0.63	116.0
	6.96	41.8	-30.0	19.2	2.23	125.0	9.7	6.5	5.3	19.5	21.6	2.96	1.60	152.0
	7.46	44.7	-41.0	22.7	2.66	126.0	13.0	9.4	7.5	19.5	21.1	2.96	2.05	162.0

TEST 3: (cont.)

	I_f	V_f	$\emptyset$	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run 7	7.68	45.8	29.0	0.0	1.45	119.0	13.3	9.7	7.9	27.5	27.8	2.96	2.08	160.5
	6.73	40.4	15.0	4.8	1.12	121.0	8.2	4.9	4.0	27.5	28.3	2.96	1.35	146.5
	4.63	28.2	0.0	6.2	0.74	119.0	1.0	0.6	0.4	27.5	28.3	2.96	0.25	103.0
	5.76	34.8	-13.0	11.9	1.40	122.0	6.8	3.2	2.6	27.5	28.9	2.96	0.91	128.0
	6.80	40.6	-20.0	16.2	1.87	126.0	9.5	6.0	4.8	27.5	29.3	2.96	1.50	148.0
	7.55	45.0	-30.0	21.3	2.45	128.0	13.8	10.2	8.1	27.5	29.9	2.96	2.14	164.5
	7.82	46.7	-40.0	24.3	2.85	127.5	18.7	13.9	11.3	27.5	30.1	2.96	2.50	171.0
Run 8	6.53	39.3	29.0	0.0	1.02	116.5	13.0	9.2	7.5	27.0	26.6	2.38	1.95	142.5
	5.25	32.6	14.0	3.9	0.64	117.0	7.5	4.0	3.2	27.0	26.8	2.38	1.03	113.0
	3.55	21.4	0.0	4.3	0.66	116.5	1.0	0.3	0.1	27.0	26.3	2.38	0.05	73.5
	4.86	29.3	-15.0	10.1	1.21	120.5	7.0	3.1	2.5	27.0	27.2	2.38	0.85	108.0
	6.55	39.6	-30.0	18.0	2.13	125.0	13.0	9.1	7.5	27.0	28.1	2.38	2.05	143.0
	5.80	47.9	-40.0	20.2	2.42	124.0	17.2	12.1	10.0	27.0	28.2	2.38	2.36	148.5
	---	4[illegible]	-48.0	21.6	2.70	124.0	20.0	16.0	13.1	27.0	28.0	2.38	2.60	152.0
Run 9	5.07	30.7	20.0	0.0	0.47	115.0	12.5	8.7	7.0	27.0	25.9	0.97	1.94	112.0
	4.02	24.8	15.0	2.1	0.13	115.0	7.0	4.0	3.0	27.0	25.9	0.97	1.10	95.0
	2.17	15.2	0.0	2.5	0.09	113.5	0.0	0.1	0.0	27.0	25.9	0.97	0.19	54.0
	3.74	22.8	-15.0	7.2	0.99	117.0	7.0	3.2	2.6	27.0	26.5	0.97	0.91	87.0
	5.00	30.2	-30.0	13.1	1.03	120.5	12.5	8.9	7.0	27.0	26.9	0.97	1.97	112.0
	5.75	32.0	-40.0	15.4	2.00	121.0	17.0	12.0	10.2	27.0	27.1	0.97	2.34	118.0
	5.4[illegible]	33.2	-49.0	16.4	2.28	121.0	20.0	16.0	13.1	27.0	27.2	0.97	2.60	122.0

TEST 4: Automatic Excitation using δ and $d\delta$ compensation with 135 ~ on stator of slip generator. V_{st} and V kept constant (not allowed to vary with line voltage).

Run	I_f	V_f	ø	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
Run 1	8.42	50.4	29.0	0.0	1.75	119.0	14.3	10.1	8.1	29.2	29.3	3.0	2.06	169.0
	7.66	46.3	20.0	4.0	1.44	120.5	9.8	6.2	5.0	29.2	29.1	3.0	1.54	155.0
	5.77	35.4	11.0	5.5	0.90	119.0	5.2	2.5	2.1	29.4	29.2	3.0	0.65	119.0
	4.94	29.9	- 7.0	8.4	1.02	119.0	3.0	1.0	0.7	29.4	29.4	3.0	0.25	101.0
	6.96	41.8	-18.0	15.8	1.85	124.0	7.9	4.6	3.6	29.3	29.4	3.0	1.20	140.0
	7.95	47.4	-26.0	20.9	2.41	126.0	12.1	7.9	6.4	29.2	29.1	3.0	1.80	159.0
	8.30	49.8	-36.0	24.9	2.85	126.5	16.7	11.6	9.5	29.0	28.8	3.0	2.25	168.0
Run 2	7.75	45.7	29.0	0	1.46	116.5	15.2	10.5	8.9	29.9	30.0	2.0	2.33	153.0
	5.82	33.5	14.0	5.3	1.06	118.0	7.0	3.9	3.1	29.7	29.9	2.0	1.18	129.0
Control	4.42	26.7	-1.0	6.5	0.78	116.5	0.6	0.1	0.0	29.7	29.7	2.0	0.24	90.0
Only Max ø	6.00	36.1	-16.0	13.2	1.56	121.0	7.0	3.9	3.1	29.5	29.5	2.0	1.06	122.0
= -36	7.47	44.3	-25.0	19.4	2.25	125.0	11.8	7.5	6.1	29.7	28.8	2.0	2.39	157.0
	7.96	47.2	-44.0	24.6	2.93	125.0	20.5	15.0	12.5	29.8	29.5	2.0	2.55	159.0
			-30.0	25.9								2.0		
Run 3	7.24	43.9	29.0	0.0	1.31	118.0	14.8	10.2	8.3	30.0	30.2	1.5	2.25	145.0
	6.56	40.1	17.5	4.3	1.11	119.0	9.2	5.6	4.5	29.9	29.8	1.5	1.58	132.0
Control	3.94	24.9	0.0	5.3	0.62	116.0	0.6	0.1	0.0	29.9	29.8	1.5	0.27	80.0
Only Max ø	5.44	32.8	-14.0	11.7	1.39	120.0	0.6	3.6	2.9	30.0	30.1	1.5	1.03	11[illegible].0
= -57	6.83	41.0	-26.5	17.7	2.07	123.0	12.2	8.0	6.3	30.0	29.9	1.5	1.90	13[illegible].0
	7.10	43.3	-35.0	20.3	2.37	124.0	16.4	11.5	9.2	29.9	30.1	1.5	2.31	14[illegible].0
	7.35	44.0	-44.0	22.3	2.66	124.5	20.7	15.5	12.5	29.[illegible]	29.9	1.5	2.60	14[illegible]
			-60.0	23.[illegible]								1.5		

Run 4	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	6.30	38.2	29.0	0.0	0.96	114.5	14.5	9.9	8.1	29.4	29.3	1.0	2.05	127.0
δ Control	5.40	32.6	18.0	2.7	0.63	115.5	9.0	5.5	4.3	29.2	29.3	1.0	1.32	111.0
only	2.84	17.7	- 1.5	3.2	0.67	113.5	0.6	0.1	0	29.0	28.8	1.0	0.10	59.0
Max ϕ= -55	4.53	27.2	-16.0	9.2	1.15	117.0	6.3	3.7	2.6	28.8	29.0	1.0	0.93	93.0
	5.84	35.0	-25.0	14.2	1.70	120.0	11.0	7.1	5.6	28.7	28.9	1.0	1.65	118.5
	6.30	37.8	-35.0	17.5	2.13	120.5	15.5	10.8	8.8	28.6	28.5	1.0	2.12	127.0
	6.56	39.0	-45.0	19.9	2.51	121.0	21.0	15.0	12.3	28.9	28.7	1.0	2.47	133.0
	6.64	40.3	-51.0	20.3	2.70	119.5	24.2	18.0	14.5	29.0	29.3	1.0	2.65	135.0
			-60.0	20.5										

Run 5	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	5.66	33.8	29.0	0.0	0.71	113.5	10.0	6.5	5.0	20.0	20.1	1.0	1.50	56.0
	4.38	27.2	16.0	2.5	0.30	113.5	5.8	2.8	2.1	20.0	20.2	1.0	0.81	91.0
δ Control	2.95	17.7	-3.0	3.5	0.63	112.0	0.4	0.1	0.0	20.0	19.9	1.0	0.15	62.0
only	3.45	20.5	-14.0	6.2	0.89	113.5	3.5	1.5	1.0	20.0	20.1	1.0	0.40	71.0
Max ϕ= -[illegible]	4.90	29.5	-25.5	12.3	1.52	118.5	7.6	4.4	3.4	20.0	20.1	1.0	1.14	102.0
	5.75	34.9	-36.0	16.0	1.95	120.0	11.0	6.9	5.4	20.0	20.0	1.0	1.64	117.[illegible]
	6.22	37.0	-46.0	18.6	2.41	121.0	14.2	10.0	7.8	20.3	20.1	1.0	2.03	127.0
	6.38	38.4	-53.0	19.7	2.30	120.5	16.7	12.0	9.5	20.3	20.1	1.0	2.23	130.0
			-62.0	20.3								1.0		

Run 6	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	6.[illegible]	39.0	29.0	0.0	1.00	116.0	9.4	5.8	4.6	19.9	20.0	1.5	1.50	130.0
δ Control	4.80	29.3	15.0	3.1	0.48	115.0	4.9	2.3	1.9	19.9	19.9	1.5	0.70	95.0
only	3.80	23.2	0.0	4.8	0.59	11[illegible].0	0.5	0.1	0.0	20.0	19.9	1.5	0.21	78.0
Max ϕ= -[illegible]	4.28	25.8	-14.0	8.3	1.05	117.0	3.9	1.6	1.1	20.0	19.9	1.5	0.50	89.0
	[illegible].70	34.8	-27.0	14.5	1.75	119.5	7.9	4.5	3.6	20.0	20.0	1.[illegible]	1.20	117.0
	[illegible].72	39.[illegible]	-37.0	19.0	2.30	122.0	11.[illegible]	7.[illegible]	[illegible]	20.0	20.0	1.5	1.77	13[illegible]
	7.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.4	[illegible]	[illegible]	19.9	[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]	2[illegible].1								1.5		

Run 7	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	7.07	42.4	29.0	0.0	1.24	114.5	9.7	6.1	4.9	20.0	19.8	2.0	1.49	141
δ Control	5.63	33.8	15.0	3.9	0.77	116.0	5.4	2.7	2.0	20.0	20.1	2.0	0.74	113
only	4.30	26.0	0.0	5.9	0.70	115.5	0.6	0.1	0.0	19.9	20.1	2.0	0.15	88
Max ϕ= -58	4.86	28.6	-12.0	8.9	1.10	117.5	3.2	1.1	0.8	19.9	19.8	2.0	0.42	98
	6.15	37.0	-23.0	15.1	1.79	121.0	7.4	4.2	3.3	20.0	19.8	2.0	1.15	126
	7.03	42.2	-30.5	19.1	2.27	122.5	9.9	6.4	5.0	19.9	20.1	2.0	1.60	142
	7.55	45.3	-40.5	22.7	2.68	124.5	13.3	8.8	7.0	20.0	20.2	2.0	2.00	152
	7.75	46.3	-48.0	24.5	2.98	125.5	15.4	10.8	8.8	20.0	20.1	2.0	2.20	156
			-64.0	25.4								2.0		

Run 8	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	7.72	46.6	29.0	0.0	1.48	116.0	9.8	6.1	4.9	20.0	20.1	3.0	1.50	155
	6.27	38.4	15.0	4.7	0.99	117.0	5.1	2.6	2.0	20.0	19.8	3.0	0.78	128
	5.05	30.4	-1.0	6.7	0.34	117.5	0.7	0.1	0.0	20.0	20.0	3.0	0.19	102
	5.22	31.9	-11.0	9.7	1.20	118.5	2.8	0.9	0.5	20.0	20.0	3.0	0.33	107
	6.07	37.1	-20.0	13.7	1.63	121.0	5.6	2.8	2.3	20.0	20.2	3.0	0.76	123
	7.36	44.7	-29.0	19.8	2.29	124.0	9.0	5.6	4.5	20.0	20.0	3.0	1.40	148
	8.06	49.2	-39.0	24.0	2.82	124.5	12.2	8.3	7.8	20.0	20.1	3.0	1.89	163
	8.30	50.8	-44.0	25.8	3.03	124.0	14.0	9.9	7.9	20.0	20.2	3.0	2.05	169

Run 9	I_f	V_f	ϕ	P	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	5.90	35.7	29.0	0.0	0.77	115.5	4.7	2.1	1.6	10.1	9.9	3.0	0.60	119
	5.40	33.0	[illegible]	3.2	0.65	116.0	3.0	1.0	0.7	10.1	10.1	3.0	0.36	110
δ Control	5.15	31.2	9.0	5.3	0.73	117.0	1.4	0.3	0.1	10.1	[illegible]	3.0	0.23	104
only	5.00	30.7	[illegible]	6.8	0.85	117.0	0.3	0.0	0.0	10.2	10.2	3.0	0.19	102
Max ϕ= -56	5.08	30.8	[illegible]	9.4	1.14	118.0	1.5	0.3	0.1	10.2	10.3	3.0	0.22	103
	5.30	32.3	[illegible]	11.8	1.44	118.5	7.0	1.1	0.9	10.2	10.3	3.0	0.36	108
	5.76	35.0	-31.0	13.3	1.57	120.0	4.8	2.3	1.7	10.2	10.2	3.0	0.52	117
	6.40	38.8	-41.0	18.9	2.39	121.0	6.4	3.5	2.7	10.2	10.3	3.0	0.93	130
	6.50	40.6	-56.0	21.1	2.76	120.5	8.0	4.8	3.7	10.2	10.3	3.0	[illegible]	137
			-61.0	22.9								3.0		

TEST 4: (cont.)

Run 10	I_f	V_f	ϕ	Γ	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	5.30	31.8	29.0	0.0	0.59	112.0	5.1	2.5	2.0	9.9	9.8	2.0	0.66	108
∫ Control	4.64	27.9	17.0	2.7	0.39	113.0	3.2	1.1	0.7	9.8	[illegible]	2.0	0.32	95
only	4.22	25.5	0.0	5.1	0.62	114.5	0.5	0.1	0.0	9.8	9.9	2.0	0.14	88
max ϕ	4.36	23.1	-10.5	7.4	0.92	115.0	1.6	0.3	0.1	9.8	9.7	2.0	0.21	89
= -58	4.54	26.6	-22.0	[illegible]	1.27	116.5	3.4	1.3	1.0	9.8	9.6	2.0	0.31	92
	4.76	29.7	-30.5	11.8	1.52	116.5	4.9	2.3	1.8	9.8	9.9	2.0	0.44	97
	5.00	34.0	-40.0	15.7	2.04	119.0	6.5	3.5	2.9	9.8	10.0	2.0	0.85	115
	6.40	33.8	-53.0	19.6	2.64	118.5	8.7	5.4	4.0	9.6	9.9	2.0	1.27	129
			-63.0	21.4								2.0		

Run 11	I_f	V_f	ϕ	Γ	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	4.64	27.4	29.0	0.0	0.10	114.0	4.5	3.0	1.5	10.0	10.2	1.5	0.56	94
	4.16	24.7	16.5	2.4	0.15	113.5	2.7	0.8	0.5	9.9	9.9	1.5	0.34	84
∫ Control	3.80	22.6	0.0	[illegible]	0.65	116.0	0.2	0.0	0.0	10.0	10.0	1.5	0.17	76
only	3.84	[illegible]	[illegible]	7.5	0.97	115.5	1.8	0.4	0.2	10.0	9.8	1.5	[illegible]	78
max ϕ	4.21	25.2	-25.0	9.8	1.30	117.0	[illegible]	1.3	1.0	10.0	9.8	1.5	0.42	[illegible]
= -57	4.77	28.2	-35.0	12.8	1.70	118.0	5.2	2.5	2.0	10.0	9.9	1.5	0.74	[illegible]
	5.47	32.2	-45.0	16.2	2.27	119.0	7.0	4.0	3.0	9.8	10.1	1.5	1.03	111
	5.94	35.5	-53.0	18.2	2.49	119.0	8.3	5.0	3.9	9.9	10.1	1.5	1.23	121
			-61.0	19.3								1.5		

Run 12	I_f	V_f	ϕ	Γ	I_L	V_L	V_{ac}	V_{dc}	I'_{f1}	V_{st}	V	I_{f1}	I_{f2}	V_o
	[illegible]	27.8	29.0	0.0	[illegible]	110.0	4.3	2.1	[illegible]	10.0	10.0	1.0	0.60	78
	[illegible]	20.4	18.0	1.5	0.1	[illegible]	2.6	0.6	0.6	10.0	10.2	1.0	0.34	68
∫ Control	[illegible]	16.5	9.0	2.7	0.4	112.5	0.9	0.2	0.1	10.0	10.2	1.0	0.20	63
only	[illegible]	[illegible]	[illegible]	[illegible]	0.76	112.5	1.2	0.1	0.6	10.0	10.2	1.0	[illegible]	62
max ϕ	[illegible]	[illegible]	[illegible]	[illegible]	1.03	113.5	3.0	[illegible]	[illegible]	10.1	10.0	1.0	0.39	[illegible]
= -50	[illegible]	[illegible]	-28.0	[illegible]	1.29	115.0	4.2	[illegible]	[illegible]	10.0	10.2	1.0	[illegible]	[illegible]
	4.47	27.8	[illegible]	11.8	1.66	[illegible]	[illegible]	3.1	2.5	10.0	10.1	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	15.7	2.21	117.0	8.0	[illegible]	4.0	10.0	10.1	1.0	1.26	[illegible]
			[illegible]	17.0										

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